2010-03

Heuristics in Global Combat Logistics Force Operational Planning

Diaz, Andres

Monterey, California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

HEURISTICS IN GLOBAL COMBAT LOGISTICS FORCE OPERATIONAL PLANNING

by

Andres Diaz

March 2010

Thesis Advisor: W. Matthew Carlyle
Second Reader: Patrick Burson

Approved for public release, distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2010	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Heuristics in Global Combat Logistics Force Operational Planning			**5. FUNDING NUMBERS**
6. AUTHOR(S) Andres Diaz			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N42, N81			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol Number ____________			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release, distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The United States Navy (USN) globally deploys to protect and sustain a peaceful international system of interdependent trade, information and social networks through a spectrum of capabilities, including humanitarian aid missions, multinational engagement, maritime domain awareness, and combat operations. In order to sustain maritime forces at sea, the Combat Logistics Force (CLF) provides logistical support via Underway Replenishments (UNREP) that maximizes deployed battle group on-station-time and endurance. We present an operational planning tool that uses a heuristic algorithm to plan Combat Logistics Force shuttle ship schedules to support forward deployed U.S. Navy battle groups operating globally. This algorithm prioritizes each battle group's replenishment requirements based on supply and determines an effective Combat Logistics Force shuttle ship pairing to execute at-sea replenishment. This determination is based on a variety of factors including range between shuttle ship and battle group, on hand commodity levels, and shuttle availability. The Replenishment-At-Sea schedules provided by the heuristic are face-valid, and can be used as initial feasible solutions for more complex and time-consuming algorithms.

14. SUBJECT TERMS			**15. NUMBER OF PAGES**
Optimization, Navy Logistics, Operational Logistics, Navy Mission Planner, Combat Logistics Force Planner, Ship scheduling, Optimization decision aid, Combat Logistics Force, Heuristics			76
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

HEURISTICS IN GLOBAL COMBAT LOGISTIC FORCE OPERATIONAL PLANNING

Andres Diaz
Lieutenant Commander, United States Navy
B.S., Florida State University, 1999

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
March 2010

Author: Andres Diaz

Approved by: W. Matthew Carlyle
Thesis Advisor

Patrick Burson, Commander, Supply Corps, USN
Second Reader

Robert F. Dell
Chairman, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The United States Navy (USN) globally deploys to protect and sustain a peaceful international system of interdependent trade, information and social networks through a spectrum of capabilities, including humanitarian aid missions, multinational engagement, maritime domain awareness, and combat operations. In order to sustain maritime forces at sea, the Combat Logistics Force (CLF) provides logistical support via Underway Replenishments (UNREP) that maximizes deployed battle group on-station-time and endurance. We present an operational planning tool that uses a heuristic algorithm to plan Combat Logistics Force shuttle ship schedules to support forward deployed U.S. Navy battle groups operating globally. This algorithm prioritizes each battle group's replenishment requirements based on supply and determines an effective Combat Logistics Force shuttle ship pairing to execute at-sea replenishment. This determination is based on a variety of factors including range between shuttle ship and battle group, on hand commodity levels, and shuttle availability. The Replenishment-At-Sea schedules provided by the heuristic are face-valid, and can be used as initial feasible solutions for more complex and time-consuming algorithms.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AOO	Area of Operations
BBLS	Barrels
BG	Battle Group
CG	Guided-Missile Cruiser
CLF	Combat Logistics Force
COA	Course of Action
COCOM	Combatant Commander
CONOPS	Concept of Operations
CONREP	Connected Replenishment
CONSOL	Consolidation
CSG	Carrier Strike Group
CTF	Commander, Task Force
CVN	Aircraft Carrier, Nuclear Propulsion
DDG	Guided-Missile Destroyer
DFM	Distillate Fuel Marine (NATO F75/76)
ESG	Expeditionary Strike Group
FFG	Guided-Missile Frigate
GAMS	General Algebraic Modeling Language
IT-21	Information Technology for the 21st Century
JP5	Naval Aviation Fuel (NATO F44)
KTS	Nautical Miles Per Hour
MOC	Maritime Operation Center
MSC	Military Sealift Command
OPCON	Operational Control
OPLAN	Operational Plan
OPREP	Operational Report
ORDN	Ordnance/Ammunition
OSD	The Office of the Secretary of Defense
NFAF	Naval Fleet Auxiliary Force
NMCI	Navy Marine Corps Internet

NWP	Navy Warfare Publication
RAS	Replenishment At Sea
SC	Surface Combatant
STNS	Short Tons
STOR	Dry Storage Commodities
T-AE	Ammunition Ship
T-AFS	Combat Stores Ship
T-AKE	Auxiliary Dry Cargo and Ammunition Ship
T-AO	Fleet Replenishment Oiler
T-AOE	Fast Combat Support Ship
TACON	Tactical Control
TRANSCOM	United States Transportation Command
UNREP	Underway Replenishments

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Operational logistics, planning, and the timely coordination of at-sea sustainment in support of the U.S. Navy's deployed battle groups is an extremely complex, dynamic, and time intensive enterprise. The Navy relies on the Military Sealift Command's (MSC) Combat Logistics Force (CLF) to serve as the principal source of resupply to all battle group logistical requirements including fuel, stores, ordnance, spare parts, and mail. To this end, fleet commanders and their staff operational logistics planners are ultimately charged with the responsibilities of battle group sustainment. This responsibility is achieved through scheduling of Replenishment-At-Sea (RAS) events within their Area of Operations (AOR) with a goal of optimal employment of CLF assets and timely delivery of resources.

Previous research and analysis efforts conducted by the Operations Research Department at the United States Naval Postgraduate School has culminated in the development of the Combat Logistics Force Planning Tool. This tool employs a Microsoft Excel© user interface, Microsoft Visual Basic for Applications (VBA), and the General Algebraic Modeling System (GAMS) language to develop feasible and optimal RAS scheduling solutions using a detailed and wide array of CLF and battle group data points.

In this study, we present a heuristic algorithm extension to the legacy CLF planning tool that will mathematically derive an initial feasible solution to the same types of CLF scheduling problems. The existing CLF model relies on the CPLEX solver engine and integer linear programming algorithms to determine optimal scheduling solutions. However, each solve run is time consuming, with a processing time for larger scenarios requiring between two to ten hours for completion, and can require five minutes to an hour just to find an initial feasible solution. On the contrary, a heuristic algorithm can provide initial feasible solutions in a matter of seconds.

Our heuristic algorithm benefits from the preexisting CLF planning tool's data input features and the ability to process information in the original CLF interface. Staff

planners benefit from the planning tool's easily readable and understood output features, including sawtooth diagrams that represent the daily battle group commodity inventories across a user-determined time horizon, detailed regional maps that display battle group and CLF navigational tracks, the sea routes network, and scheduled events. This tool can be used to quickly evaluate almost any global CLF scheduling scenario and offers a marked improvement to current manual planning practices.

ACKNOWLEDGMENTS

This work is dedicated to my parents; German and Luz Marina Diaz, whose immeasurable work ethic, years of self-sacrifice, and unwavering support have opened countless opportunities for success in my life. I only hope they can look back at this accomplishment with great pride, and know that everything that they have ever done for me has not been in vain or taken for granted. Mom and Dad, you epitomize the "American Dream."

I want to extend my sincerest gratitude to Associate Professor W. Matthew Carlyle for your expert tutelage, keen insights, and countless hours of assistance in successfully completing this journey. Your guidance and effort will be forever appreciated. Special thanks to CDR Patrick Burson for graciously accepting the challenge of becoming my second reader; and his first thesis student. I have enjoyed and will miss all of our conversations. I hope to see you again out in the fleet.

My most heartfelt admiration and appreciation goes out to my beautiful and loving wife, Jennifer. This thesis would never have been completed without your love, support, encouragement, and understanding. To my Lauren, Jack, and sweet Caroline, although you do not understand this now, coming home to your smiling faces every day made it all worth it, I love you. I am truly blessed to have such a wonderful family.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. OVERVIEW

The Navy’s Military Sealift Command (MSC), a subordinate command of the United States Transportation Command (TRANSCOM), operates the Naval Fleet Auxiliary Force (NFAF) that is the primary source of supply to underway U.S. Navy (USN) warships. This fleet is charged with the at-sea delivery of all logistical commodities including fuel, stores, ordnance, spare parts, and mail. The newest class of NFAF Combat Logistics Force (CLF) ship is the modular dry cargo and ammunition ship, USNS LEWIS AND CLARK class (T-AKE 1), which the Navy started phasing into service in June 2006. The LEWIS AND CLARK class was acquired to replace the aging KILAUEA class (T-AE 26) ammunition ships, MARS class (T-AFS 1), and SIRIUS class (T-AFS 8) combat stores ships. The Navy’s T-AKE program will procure fourteen units and has a budget in excess of $6 billion (NAVSEA, 2010). Additionally, the planned future CLF fleet for 2014 includes fifteen HENRY J. KAISER class T-AOs and four SUPPLY class T-AOEs (NAVSEA, 2010). The T-AKE acquisition program resides within the Navy's Program Executive Office, Ships—Support Ships Boats and Craft Program Office (PEO Ships/PMS325). For ease of exposition, we use “CLF” as the convention to describe NFAF units.

A central goal of the Combat Logistics Force is to provide the U.S. Navy a reliable replenishment at-sea capability while minimizing life cycle operating costs. The Chief of Naval Operations Strategic Mobility and Combat Logistics Division (OPNAV N42) presented an analysis problem to ascertain the most efficient employment of existing CLF units that would maximum logistical sustainment to all at-sea deployed forces. To assist in solving this problem, there is a need for the development of a robust CLF planning tool capable of scheduling CLF replenishment events to customer battle groups based on their daily activity, commodity inventory levels, and voyage plans as inputs.

Sustainment of a deployed BG is a highly complex and dynamic enterprise. Fundamental factors must be taken into consideration when planning replenishment operations to ensure feasibility of CLF support. Such factors include time-distance checks, availability of CLF assets, available commodity inventory to meet end-user demand, voyage activity of both the CLF and BG, and commodity urgency of need. All of these aspects must be aggregated throughout a predetermined time horizon and evaluated for each day of at-sea operations. Additionally, special consideration must be given to geographic constraints such as the proximity of logistics support hubs and established sea routes that capture shipping tracks and transit voyage plans. Attempted execution of infeasible CLF support schedules to forward deployed BGs can have severe, mission-compromising impacts to the operating forces. These deficient schedules can be either mitigated or outright avoided through the employment of the CLF planning tool.

B. USE OF NON-ANALYTICAL METHODS FOR UNDERWAY REPLENISHMENT SCHEDULING

Currently, only rudimentary methods are employed by fleet operational logistics planners to schedule and track Replenishment-At-Sea (RAS) and Commodity Consolidation (CONSOL) events within an AOR. Combat Logistics Force schedulers typically use basic tracking tools such as hand written charts, maps, tracking boards that are manually updated, and computer based spreadsheets, such as Microsoft Excel©, for situational awareness of CLF and BG status. The combatant ship schedulers, who typically work independently from the logistics planners, also use similar methods to track BG status information.

Fleet planners rely on daily Operational Report (OPREP) feeders released from the CLF ships and combatants under their respective fleet's Operational Control (OPCON) for updates to unit's logistical and operational status. OPREP feeders provide detailed information regarding the ship's geographic position, fuel levels, stores status, ordnance inventory, and other critical supply details. This data is subsequently used to manually update the staff planner's tracking tools. Additionally, the planners utilize the WebSked fleet scheduling interface to determine future schedules. As defined by its developer, FGM, Inc., "WebSked offers an integrated, homogenous solution for schedule maintenance that improves schedule timeliness and accuracy. Designated as the Fleet's primary scheduling tool, it is the authoritative source of Naval scheduling data" [FGM, 2010]. Properly maintained, WebSked provides strategic-level information regarding a ship's upcoming activities, such as projected geographic AOR, significant upcoming exercises and events, and anticipated ports of call. Planners use the combination of these tools to develop complementary logistics support plans, though they are not as robust nor do they provide the level of detail available with the CLF planning tool. These methods are non-automated, prone to human error, and time consuming. More importantly, scheduling based on these methods is not quantitatively based and limited in usefulness for forecasting the future operational and tactical status of ships.

C. PRIOR CLF OPTIMIZATION RESEARCH AND PLANNER DEVELOPMENT

1. Optimizing the Number and Employment of Combat Logistics Force Shuttle Ships, With a Case Study of the T-AKE Ship

Borden [2001] takes a first look at implementing mixed integer program (MIP) models to schedule CLF CONSOLS. His model was developed and used to evaluate the CLF force level and capabilities. More specifically, it determined whether the current CLF force composition was capable of sustaining BGs in various, logistically demanding scenarios. His analysis took into account single and multiple BG sustainment events, and also varied the operational intensity and magnitude of these scenarios. His research further delved into analysis of the T-AKE capabilities and demonstrated the need to tailor T-AKE commodity load-out configurations for service to specific BGs. His analysis also demonstrated the effects of adjusting the transit times between shuttle ships, station ships, and BGs.

2. Optimizing Global Operations Plans for the Combat Logistics Force

Cardillo [2004] analyzes a CLF sustainment support scenario based on the global deployment of all available USN combatants. This study illustrated the capacity available to sustain a major theatre contingency operation, then reacting to the demands of a second, subsequent major theatre contingency. His analysis demonstrates the advantages of planning CLF commodity load outs based on supporting a BG's forecasted daily requirements vice using the average daily demand data, as the traditional basis for determining fleet requirements. Although an average demand may adequately serve as a baseline for projections, customizing a load-out plan based on anticipated employment provides improved fidelity to CLF cargo requirements. Most importantly, average daily demand does a poor job of capturing variability, possibly resulting in the depletion of replenishment stocks. His results demonstrated that supplementary logistical support would be required to ensure BGs did not fully consume theater stocks of Distillate Fuel Marine (DFM).

3. Optimization of Combat Logistics Force Required to Support Major Combat Operations

Morse [2008] examines the combination of the CLF planning tool and a scenario builder interface to evaluate the optimal distribution of CLF forces in support of a combat scenario in a predetermined AOR. More specifically, his model calculated the minimum number of CLF ships required to sustain a large naval force conducting operations in a major theater contingency. Another key feature identified in his modeling is the tradeoff between CLF shuttle ships versus CLF station ships. As defined, shuttle ships carry commodities from a source of supply and will transfer them via at-sea CONSOL event to station ships that remain on location with the BG. In turn, the station ships will distribute the commodities throughout the BG via underway replenishments (UNREPs). He also outlines the significance that resupply ports locations have on BG resupply and CLF assets. Morse concludes that the information provided through the scenario builder interface to decision makers was of great usefulness to fleet commanders and planners. This data gives decision makers better fidelity of overall fleet demand requirements and can be used to make more informed force structure decisions.

4. Optimizing Operational and Logistical Planning in a Theater of Operations

Hallmann [2009] further refines the CLF planner to improve its reliability as a viable decision tool to fleet commanders and planners. His work develops an aid that solves feasible CLF deployment schedules that will satisfy BG logistics demand requirements without restricting the BG Operational Plan (OPLAN). The CLF planning tool improvements allow planners to calculate optimal CLF schedules through a predetermined time horizon. Hallman employed the CLF planning tool during the real-world exercise TRIDENT WARRIOR 2009. The scenarios in this exercise generated mixed integer programs with 5,500 constraints and 6,000 variables. Using GAMS and the CPLEX solver, optimization solutions were available in approximately four minutes, determining CLF employment plans and quantities of each commodity to be transferred to a BG. Hallman concludes that optimal CLF solve times will typically vary from 5 to 10 minutes, based on the level of complexity of the scenarios evaluated; however, the CLF planner outputs provide time and flexibility for commanders and planners to make better informed fleet employment decisions and formulate future plans.

The Combat Logistic Force Planning Tool is the result of a culmination of years of previous research effort and preceding thesis study at the United States Naval Postgraduate School, Monterey, CA. Through the use of Visual Basic for Applications (VBA) and General Algebraic Modeling System (GAMS) programming techniques, user provided data and constraints are evaluated to provide feasible and optimal results. The CLF planner output is displayed in a user-friendly format using a Microsoft Excel© interface, offering an uncomplicated visual representation of results for the fleet planners and operators.

Currently, a modified versions of Hallman's model is in use at the OPNAV N42 to perform a zero baseline review of the CLF. The scenarios in that analysis are so large that each run can take several hours to generate results.

D. OBJECTIVES

In its current form, the CLF planning tool is not accessible by fleet commanders and planners using standard Navy Marine Corps Internet (NMCI) computers ashore or Information Technology for the 21st Century (IT-21) computers at sea. Both IT systems have significant restrictions regarding the installation of specifically configured software such as GAMS, which is integral to powering the CLF planner. Additionally, GAMS uses a commercial integer-programming solver (CPLEX) to solve the optimization models, which requires user license agreements that make installation and support, on a large scale, cost prohibitive. Considering these limitations, the objective of the current thesis is to add a heuristic algorithm to the CLF planner that would circumvent the requirement for the GAMS solver. Moreover, the goal of our heuristic is to leverage Microsoft VBA for code programming, which is typically packaged together with Microsoft Excel© and included in the NMCI and IT-21 software bundles. The refinement we have created will allow fleet commanders and staff planners to use existing technologies for determining and reasonable feasible solutions to CLF scheduling problems without the added cost requirements of specialized programs and stand-alone, non-networked computers.

An added benefit of our heuristic algorithm is the anticipated quicker solve time for a feasible solution, as compared to the traditional optimization model in the CLF planning tool. On problems of realistic size, the heuristic algorithm determines initial feasible solutions in a matter of 1 to 2 seconds, as compared to the optimization model requiring from 10 minutes to an hour to generate a feasible solution. This improves processing time by orders of magnitude, providing results in a timelier manner to mission planners. The obvious tradeoff is made between quickly finding an initial feasible solution with heuristics versus determining an optimal solution using the traditional tools and GAMS. The added benefit of using heuristics, however, is that the initial feasible solution can then be fed into CPLEX as a starting point, avoiding the frequently costly processing used by its root-node heuristic.

The decision aid we have created provides operational and logistic staff planners enhanced fidelity over BG logistical status and serve as a forecasting tool for sustainment demands to the fleet commander. The tools presented in this work were evaluated in stressful mission scenarios provided by the Office of the Secretary of Defense (OSD), specifically using data from TRIDENT WARRIOR 2009.

We evaluated the heuristic algorithm presented in this thesis under the stressful real world data set representative of the scope and scale of TRIDENT WARRIOR 2009. Using this large-scale scenario offers an exact comparison against preexisting CLF planning results that were derived using optimization tools. Moreover, we also assess our heuristic functionality over two smaller, notional support scenarios where its initial feasible solutions are measured against optimal solutions derived using CPLEX and GAMS to determine its usefulness as an alternate means of formulating CLF logistics support plans.

THIS PAGE INTENTIONALLY LEFT BLANK

II. COMBAT LOGISTICS FORCE PLANNING TOOL AND HEURISTICS SUBROUTINE

A. CLF PLANNING TOOL INTRODUCTION

The CLF planning tool was originally designed to assist decision makers in formulating logistics sustainment plans in support of all deployed BGs anywhere in the world during a predetermined time horizon. It determines which CLF will replenish which BG, and how much inventory of each commodity is to be transferred, in each day of that planning horizon. Furthermore, the CLF planning tool ensures that each BG maintains positive commodity inventories, and it determines feasible sustainment scheduling plans. This tool uses mixed integer linear programming to optimize the scheduling of all available CLF ships based on such factors as, but not limited to, CLF availability, time-distance to BG, commodity consumption rates, and location of regional logistics hubs. The CLF planning tool relies on a preprogrammed, fixed sea routes network that captures navigable surface tracks, identifies transit waypoints, and logistical hubs in the numbered fleets, which fall under the responsibility of one of the COCOMs.

Figure 1. Global Unified Commanders' Areas of Responsibility. From the National Geospatial-Intelligence Agency (2008).

The CLF planner overlays actual BG transit tracks onto the sea routes network and then used to construct the respective supporting CLF transit tracks. The Floyd-Warshall algorithm is then executed to calculate the shortest paths between BG, CLF, and logistics hubs. These paths are used to determine the feasibility of CLF schedules.

B. COMMODITIES

The CLF planning tool focuses on the delivery of four key commodities: Distillate Fuel Marine (DFM or NATO F-76), Naval Aviation Fuel (JP-5 or NATO F44), dry subsistence stores (STOR), and ordnance (ORDN). The Navy Warfare Publication, Sustainment At Sea (NWP 4-01.2), "provides operational logisticians, line officers, and logistics planners an in-depth overview of the organizational framework and structure of Navy sustainment at sea." More specifically, NWP 4-01.2 provides important planning factors such as commodity and ship-type specific consumption rates, as well as USN and MSC ship commodity capacities, commodity specific consumption rates, and CLF capabilities by hull type, Table 1.

Ship	Speed	Max Speed	Operational Radius	TEU's	Ro/Ro sq ft	Dry Cargo Stons	Ord Stones	Cargo Fuel bbls
T-AOE	26	26	3,000	0	0	952	2016	156,000
T-AKE	20	24	14,000	0	0	1963**	3647**	23,450
T-AE	20	20	10,000	0	0	0	4928	18,674
T-AFS	21	21	10,000	0	0	4600	0	18,674
T-AO	17	20	3,000	0	0	220	0	154,200/180,000
MPF	20	24	6,000	115	144,000	1,336	260	36,000
T-5 Tanker	15	20	6,000	0	0	0	0	237,766
JHSV	40	49*	1,250	52	25,000	390	585	0

* empty seed
**This represents a possible (standard) 35/65 percent split for Dry Cargo and Ordnance. In reality, these loads can be split differently

Table 1. Details of the capabilities and limitations of the various Combat Logistics Force ships, including their cargo capacities across all of the key commodities. (Taken from NWP 4-01.2).

The storage capacities of the various USN warships for each of the major commodities are provided in the following table, Table 2.

Ship	DFM (Bbls)	JP5 (Bbls)	Stores(Stons)	Ord (Stons)	Navy or USCG Personnel	USMC/Other Embarked Personnel
CVN	0	74642	1710	1765	5680	0
CV	54283	45124	1247	1765	5624	0
CG47	15032	475	68	94	374	0
DDG51	10518	475	55	48	363	0
FFG7	4286	475	35	16	227	0
SSN	0	0	25	126	120	0
LCS (GD)	4276	656	5	20	70	0
LCS (LM)	2663	579	5	20	70	0
LHD	43091	14452	520	391	1123	1850
LHA	45125	10450	641	391	930	1713
LPD4	17700	443	187	88	408	800
LPD17	23750	6785	195	88	261	800
LSD41	19150	1144	140	38	346	450
SSGN	0	0	35	Mission Dependent	159	66 SOF
USCG WHEC Cutter	5357	178	52.7	33	167	0

Table 2. Storage capacities of the various USN vessels for each of the key commodities. (Taken from NWP 4-01.2)

In the CLF planner, each of these commodities is assigned a precedence factor that is later used to formulate an urgency of need prioritization for BGs. Since each of these planning factors has a significant impact on the sustainability of a BG, they are tracked and evaluated on a day-by-day basis. It is important to note that the consumption factors of BG commodities will vary and are susceptible to changes and fluctuations for any number of reasons, including alterations to mission requirements, weather variances, shifts in wind and sea state, material readiness, and human factors.

In order to prioritize BG by urgency of need, penalties are assigned to remaining stock levels of each specific commodity for each day along the time horizon. Each commodity has an associated precedence or priority factor as input during the model implementation. Planners using the CLF planning tool can adjust these scalars based on their utility, or values deemed most important for that particular theater or scenario. Commodity inventories falling below the predefined safety stock levels have a corresponding safety stock penalty associated with them, and inventories falling below the predetermined “extremis level” incur larger penalties as the inventory position worsens. Lastly, if a commodity stock level were to reach zero (or below) on-hand quantity, the magnitude of the corresponding penalty intensifies tremendously. Realistically, if a commodity such as DFM were to reach a zero or negative balance, that ship would be dead in the water. This situation is permitted to occur in the model for bookkeeping purposes and ensure the planning tool only generates feasible outputs. These various penalties can be adjusted for each day on the planning horizon. So, as commodity inventory levels worsen, their penalties are amplified by orders of magnitude. These penalty values are scaled based to each commodity, in turn, establishing the urgency of need for each deployed BG. Consequently, if any feasible plan exists that keeps all inventories positive, our models will find it. Given feasibility, we will prefer to keep all BGs above extremis, and then above safety stock, as possible.

C. EMPLOYMENT FACTORS

The CLF planning tool captures each individual ship's daily consumption rates based on the spectrum of daily activities, such as combat operations, flight operations, transit, etc. Clearly, operational employment will influence fuel consumption rates and impact overall BG fuel demand. Therefore, this data is then aggregated for the entire BG to recalculate total daily logistical requirements. NWP 4-01.2 provides baseline consumption figures for various BGs, offered as examples in Table 3 (CSG), Table 4 (ESG), and Table 5 (SSG).

Daily POL Requirements					
Ship Type	POL Type	Capacity (bbls)	Pre-Assault Rate (bbls/day)	Assault Rate (bbls/day)	Sustain Rate (bbls/day)
CVN	DFM	-	-	-	-
	JP5	74,642	3,000	5,000	4,000
CG	DFM	15,032	1,429	757	757
	JP5	475	5	39	19
DDG-51	DFM	10,518	1,200	646	646
	JP5	475	5	34	19
Station Ship Cargo Capacity					
T-AOE	DFM	62,400*	2,570	960	960
	JP5	93,600	10	10	10

*assumes 40/60 split

Daily Dry Requirements				
Ship Type	Cargo Type	Load-Out (stons)	Assault Consump. (stons)	Sustain Consump. (stons)
CVN	Stores	1,710	53	53
	Ordnance	1,765	150	100
CG	Stores	68	2	2
	Ordnance	94	5	3
DDG-51	Stores	55	2	2
	Ordnance	48	3	2
Station Ship Cargo Capacity				
T-AOE	Stores	952	1	1
	Ordnance	2016	0	0

Table 3. Sample Carrier Strike Group daily consumption rates of the key commodities tracked during three general phases of operations, Pre-Assault, Assault, and Sustainment. (Taken from NWP 4-01.2).

Daily POL Requirements					
Ship Type	POL Type	Capacity (bbls)	Pre-Assault Rate (bbls/day)	Assault Rate (bbls/day)	Sustain Rate (bbls/day)
LHD	DFM	43,091	2,000	1,071	1,071
	JP5	14,452	72	759	512
LPD	DFM	23,750	1,142	528	528
	JP5	6,700	17	324	221
LSD	DFM	19,150	725	346	346
	JP5	1,144	2	81	55
DDG-51	DFM	10,518	1,200	646	646
	JP5	475	5	34	19
LPD-17	DFM	19,061	1,142	1,071	1,071
	JP5	7,563	17	759	512

Daily Dry Requirements				
Ship Type	Cargo Type	Load-Out (stons)	Assault Consump. (stons/day)	Sustain Consump. (stons/day)
LHD	Stores	520	15	15
	Ordnance	391	33	18
LPD	Stores	195	5	5
	Ordnance	88	6	4
LSD	Stores	140	4	4
	Ordnance	35	2	1
DDG-51	Stores	55	2	2
	Ordnance	48	3	2
LPD-17	Stores	210	6	6
	Ordnance	513	6	4

Table 4. Sample Expeditionary Strike Group daily consumption rates of the key commodities tracked during three general phases of operations, Pre-Assault, Assault, and Sustainment. (Taken from NWP 4-01.2).

Daily POL Requirements				
Ship Type	POL Type	Capacity (bbls)	Assault Consumption (bbls/day)	Sustain Consumption (bbls/day)
CG	DFM	15,032	757	757
	JP5	475	39	19
DDG-51	DFM	10,518	646	646
	JP5	475	34	19
FFG	DFM	4,286	304	304
	JP5	475	39	19
LCS (5/squadron)	DFM	4,276	480	360
	JP5	656	29	19

Daily Dry Requirements				
Ship Type	Cargo Type	Load-Out (stons)	Assault Consumption (stons/day)	Sustain Consumption (stons/day)
CG	Stores	68	2	2
	Ordnance	94	5	3
DDG-51	Stores	55	2	2
	Ordnance	48	3	2
FFG	Stores	35	1	1
	Ordnance	16	1	.75
LCS (5/squadron)	Stores	5	.25	.25
	Ordnance	20	2	1

Table 5. Sample Surface Strike Group daily consumption rates of the key commodities tracked during three general phases of operations, Pre-Assault, Assault, and Sustainment. (Taken from NWP 4-01.2).

D. RECENT CLF PLANNING TOOL ADVANCES AND FEATURES

The original sea routes network was comprised of 182 nodes, 187 fast arcs and 11 slow arcs, where the difference between a fast and slow arc is an adjustment for geographic constraints or choke points that require slow transit speeds. For example, sailing through the Panama or Suez Canals takes significantly longer than an unencumbered transit of the same length in open ocean waters. The latest iteration of the CLF planner consists of 310 nodes, 577 fast arcs, and 10 slow arcs, including 145 ports [Hallman, 2009]. An example of this latest sea routes network with extended fidelity introduced by Hallman is illustrated in Figure 2.

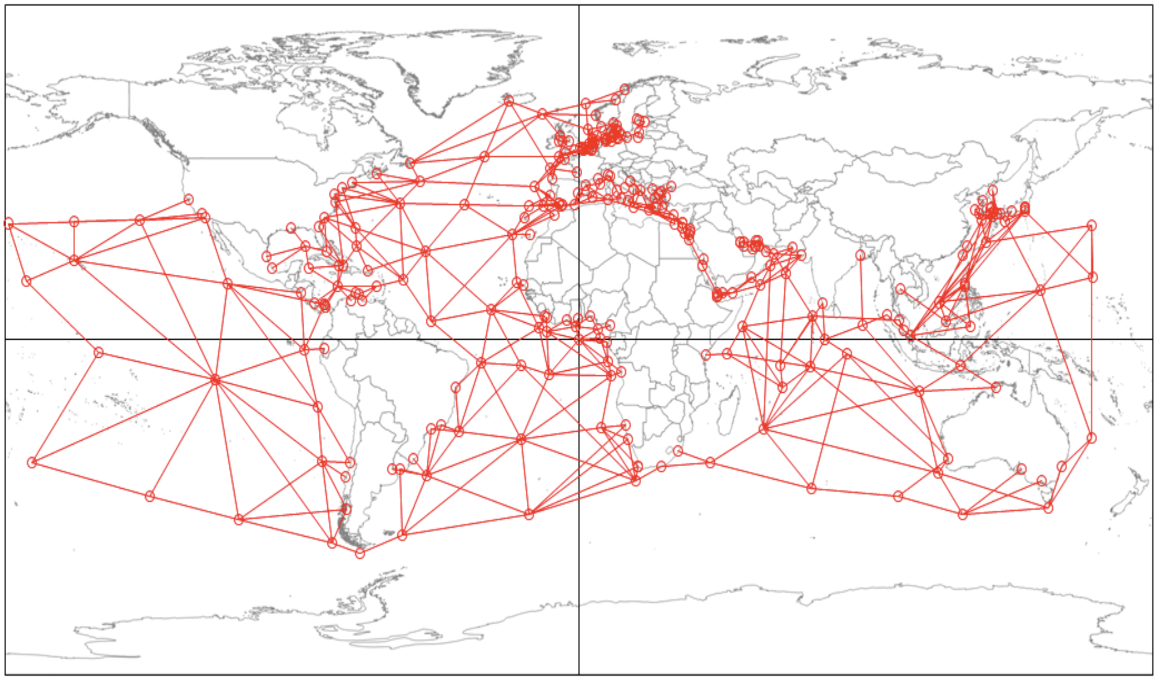


Figure 2. Extended static sea routes network demonstrates the worldwide transit tracks that Combat Logistics Force ships can traverse from logistics ports to battle groups to execute Replenishment At Sea events. Figure from Hallman (2009).

A catalog listing of all active USN ships and supporting CLF ships by individual hull number and name has also been added to the planning tool. This feature allows users to select specific CLF ships, combatants, and BGs for operation in a specific AOR [Hallman, 2009]. When running the optimization tool, this reduces computational complexity and, therefore, computer run time needed to determine an optimal scheduling solution. This functionality also allows planners to select and deselect ships that enter or leave the scenario throughout the time horizon as well, further reducing the computational complexity of the scheduling problems by omitting irrelevant ships from the equation.

The CLF planning tool features a user-friendly output interface, or "dashboard," using Microsoft Excel©. This interface features all relevant information for each day on the planning horizon. In the most recent update, additional maps have been added for improved geographic visual representations of operations around the world. These twenty-one maps depict nodes, arcs, logistics hub ports, and navigational tracks used by

BGs and CLFs. The dashboard also allows the user to pinpoint the exact geographic position of replenishment events anywhere in the world. Lastly, a map animation feature has been improved to offer a dynamic visual representation of day-to-day BG and CLF ship movements along their tracks [Hallman, 2009].

E. SCENARIO INFORMATION

1. TRIDENT WARRIOR 2009

The CLF planning tool was selected by the Navy Warfare Development Command (NWDC) to be tested by the Maritime Operation Center (MOC) during the exercise, TRIDENT WARRIOR 2009. This exercise simulated fleet operations in two separate AORs, with a goal of improving the interoperability between the regional MOCs. This exercise featured seventeen BGs made up of thirty-four different combatants of various classes, six CLF ships, operating over a 180-day time horizon, near the Gulf of Guinea, the Caribbean Sea, Mediterranean Sea, and Eastern U.S. Atlantic waters [Hallman, 2009]. The data collected from this stressful scenario is evaluated using the heuristic presented in this thesis. These results are analyzed and compared to output derived using Hallman's optimization.

2. Supplemental Scenarios

In addition to the complex scenario presented by the TRIDENT WARRIOR 2009 exercise, multiple smaller scale scenarios are developed and simulated to test the heuristic algorithm. Although these scenarios are scaled down in complexity, the resulting data output is expected to be more representative of the level of support required during normal day-to-day peacetime operations in an AOR. Fleet commanders and planners can then use this information to forecast the level of CLF support required given the number of USN ships operating in their AOR at any given time.

3. Scenario Assumptions

In order to develop the above scenarios, certain assumptions have been factored into the modeling portion of this research.

- Each BG will have a station ship assigned to it that will CONSOL with the CLF shuttle ship. This station ship will receive all demand requirements for the BG for further distribution to the individual combatants. The CLF shuttle ship will not interact with the individual USN ships.
- CLF shuttle ships will transit at the most economic (fuel conserving) speed between CONSOLs and logistics ports.
- BGs will receive the minimum of either their respective available capacity for each commodity (demand) or maximum stock available onboard the servicing CLF shuttle ship during a CONSOL.
- With the exception of port commodity restrictions, CLFs will leave logistics ports at 100% inventory for each of the planning factor commodities or maximum available.
- At-sea replenishment of BGs is prioritized over refueling in port.
- Unless specified, CLF and BG ships will experience no unplanned losses through the course of the scenarios.
- Unless a commodity's stock level falls below safety stock or extremis stock level, BGs will be limited to one CONSOL during any consecutive four-day period.

THIS PAGE INTENTIONALLY LEFT BLANK

III. MODELING THE CLF PLANNING TOOL WITH HEURISTIC FUNCTIONALITY

A. PREVIOUS CLF PLANNER MODEL FORMULATION

The Appendix reproduces Hallman's [2009] optimization formulation for the CLF planning tool. The heuristic formulation we present recycles elements used in Hallman's formulation, including variable names and data structures. The following heuristic formulation we present is a byproduct of extending the functionality of the preexisting programming structure and ensures the compatibility of the heuristic algorithmic coding introduced in this thesis. Hallman's formulation is referenced as applicable. Refer to either Appendix or Hallman [2009] for more additional formulation details. For the ease of exposition, the data structures presented below will be written in GAMS notation versus a mathematics format primarily because the number and length of the indices make this format easier to read.

B. EMBEDDED HEURISTIC FUNCTIONALITY AND DATA STRUCTURES

1. Sawtooth Diagram

A sawtooth chart shows on-hand quantities of cargo and provides a visual indication of consumption rates and cargo transfer amounts. The sawtooth chart can display individual BG commodities or a more robust, aggregated multi-commodity representation of the day-to-day levels of a commodity inventories on one screen. It also displays each BGs respective commodity capacity, safety stock level, and extremis stock level. Moreover, the sawtooth diagram can also be used to depict the inventory levels of a specific commodity for multiple BGs throughout a predetermined time horizon. This capability makes it easy to determine which, if any, BG would be in danger of having a commodity inventory level fall beneath safety stock or extremis levels, and on what days that would occur. This is all controlled by planners using drop down menus and lists in the CLF planning tool user interface on Microsoft Excel©. The following figure is a direct representation of the DFM inventory levels spanning across all BGs participating in TW09 through out the 25 June 09 through 13 August 09 time horizon, Figure 3. In this particular worldwide scenario, the BGs were supported by a total of six CLF shuttle ships of varying classes. The CLF planning tool's dashboard board features a drop down menu to select individual BGs and specific commodities for alternate data representation to include markers delineating the specific safety stock and extremis stock boundaries.

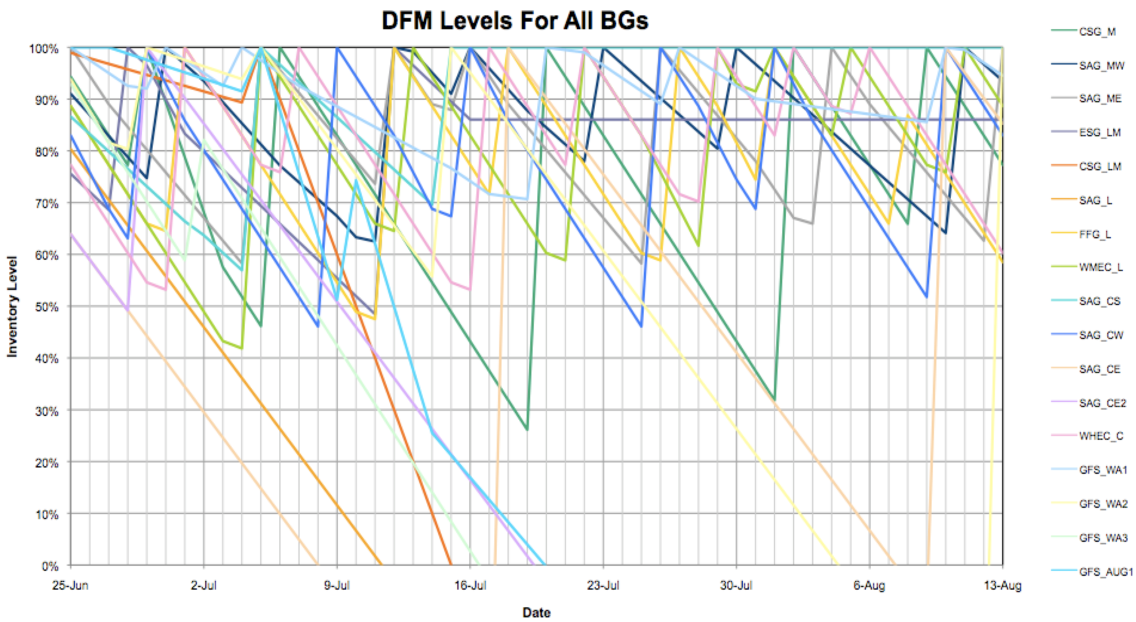


Figure 3. Sawtooth diagram that displays the DFM inventory levels of all the battle groups participating in TRIDENT WARRIOR 2009. Areas of Operation included the Eastern Atlantic Ocean, Gulf of Guinea, Caribbean, and the Mediterranean.

2. Battle Group Inventories

The inventories of each individual ship in each battle group are aggregated into the bg_inv(bg, c, d) array. More specifically, for every battle group, this structure holds the remaining stock level of each specific commodity for the entire battle group on a particular day. We track stock levels in terms of current inventory for each commodity. To derive 'days remaining,' we would consider the current inventory level and the specific consumption numbers in the immediate future. This gives a much more accurate indication of inventory remaining than simply dividing the current inventory by the current, but transitory, consumption rate. For the purposes of the CLF planner, the commodities that are tracked on the sawtooth diagram are DFM (Diesel Fuel Marine) (c_1), JP-5 (Jet Fuel) (c_2), STOR (Stores) (c_3), and ORDN (Ordnance) (c_4). Of note, the planner can also be extended to capture additional types of commodities as required. This data structure is illustrated in Table 6.

Commodity ($c_1, c_2, \ldots, c_n$)	**Inventory Level On Day ($d_1, d_2 \ldots, d_n$)**			
	d_1	**d_2**	**d_3**	**d_4**
DFM, c_1 (Bbls)	54283	50671	46546	41423
JP-5, c_2 (Bbls)	45124	39876	34291	29647
STOR, c_3 (Stons)	1710	1503	1289	1076
ORDN, c_4 (Stons)	1765	1688	1611	1545

Table 6. Daily commodity, c, inventory level for one sample, bg = CSG_M, bg_inv(bg, c, d).

The daily consumption factors that vary with each BG's individualized consumption rates are read into the consume array, consume(bg, c, d). BG consumption rates will change with voyage plans and changing activities. These consumption figures are subtracted from each respective BG's daily inventory to reflect the most accurate requirements data.

Pre-determined fixed data points for each of the respective commodity stock storage capacities, safety levels, and extremis levels are programmed into the model. Each BG is assigned a capacity, cap(bg, c), safety level, safety(bg, c), and extremis level, extremis(bg, c) for each of the tracked commodities. Operational or logistical commanders have the ability to tailor these data points to most accurately reflect each of the BG's capabilities and limitations prior to executing the CLF planning tool. A visual representation of these structures is displayed in Table 7.

Commodity ($c_1, c_2, \ldots, c_n$)	**Capacity** cap(bg,c)	**Safety Level** safety(bg,c)	**Extremis** extremis(bg,c)
DFM, c_1 (Bbls)	54283	27142	16285
JP-5, c_2 (Bbls)	45124	22562	13537
STOR, c_3 (Stons)	1247	624	375
ORDN, c_4 (Stons)	1765	883	530

Table 7. Example commodity stock data for a sample battle group, bg. This data is entered into the CLF planner by operational commanders and/or logistics planners.

In order to break out the most important commodities based on mission and logistics requirements, the CLF planning tool offers planners the ability to customize the weight, or degree of importance, of a commodity. For instance, if DFM is the most restrictive commodity to mission success, planners can set its weight, which is a scalar, at a much higher value than a commodity that is not as restrictive, such as STOR. Since these weight priorities are customizable, the applicability of the CLF planning tool broadens significantly. The effect of the weights becomes more apparent as they are used to scale bg commodity inventory levels in the penalty portion of the formulation, which in turn determines which bg holds the highest priority to receive a shuttle ship replenishment. These weight values are assigned to the priority values structure, priority (c). An example of this array is offered in Table 8.

Commodity ($c_1, c_2, \ldots, c_n$)	Priority priority(c)
DFM, c_1	9
JP-5, c_2	10
STOR, c_3	7
ORDN, c_4	6

Table 8. Assignment of commodity priority values, priority(c). In this case, the most restrictive commodity is JP-5, and therefore, weighted with the highest scalar value.

3. Shuttle Ship Cargo Inventories

The array s_inv(s, c, d) is initialized to track each of individual shuttle ship's daily commodity inventory. Similarly to the bg_inv(bg, c, d) inventory array, this data structure affords the heuristic algorithm the ability to determine each specific commodity level aboard a shuttle ship any day of the time horizon. The stock levels assigned to the s_inv(s, c, d) are in terms of actual stock volume, vice days of stock remaining per commodity. It is important to realize the relevance of the classes of CLF ships serving as shuttle ships. Some classes of CLF have inherent limitations such as the absence of weapons magazines, which preclude their ability to shuttle ordnance. An example is Henry J. Kaiser class T-AO, fleet replenishment oiler, which is incapable of storing ordnance onboard and therefore have zero impact on bg ORDN demands. This data structure appears in Table 9. Our heuristic algorithm has a built in feature that forces the shuttle ships to pull into a logistics port once a commodity inventory level falls below a preset percentage of commodity capacity. Our initial analysis is done with a preset level of 20% of initial commodity capacity, which can later be adjusted by logistical planners or operational commanders.

Commodity ($c_1, c_2, \ldots, c_n$)	**Shuttle Ship Cargo Inventory Level On Day** ($d_1, d_2 \ldots, d_n$)			
	d_1	**d_2**	**d_3**	**d_4**
DFM, c_1 (Bbls)	84000	68000	68000	54000
JP-5, c_2 (Bbls)	76000	58000	58000	49500
STOR, c_3 (Stons)	952	765	765	470
ORDN, c_4 (Stons)	2016	1850	1850	1690

Table 9. Daily commodity, c, cargo inventory level for each shuttle ship, s, s_inv(s, c, d).

4. Cycledays Data Structure

One of the most critical data structures incorporated in the CLF heuristic algorithm is also used by the integer programming formulation; the parameter cycledays(s, bg, d, p, bx, dx) indicates the number of days required for shuttle ship s to travel from the location of the battle group bg on day d to reach the location of battle group bx on day dx while visiting port p in between. If this travel time is greater than the number of days between d and dx, then this combination of replenishment visits and port is not possible for shuttle ship s. The key calculation to determine the travel times between the bg location, ports, and subsequent bx location is a shortest path on the available sea routes. These calculations are already provided by the CLF planning tool. Note that a direct route between consecutive battle groups is also evaluated for each iteration, where the direct option is considered an intermediate port without an in port turn around time. In order to reduce the data requirements of the algorithm, we explicitly list every cycledays(s, bg, d, p, bx, dx) combination that is not feasible, based on the cycledays calculation. Although this labeling may seem counterintuitive, by explicitly listing only the combination of events that are infeasible, we significantly reduce the data requirements and therefore minimize the time required to calculate solutions. The detailed formulation for cycledays is referenced from the Appendix.

5. Shuttle Ship Assignment Data

To assign shuttle ships to the highest priority BGs, we now define additional data structures critical to prioritizing CONSOL events by urgency.

$thisS$	An integer value that holds the shuttle with the shortest range to highest priority bg.
$thisBG$	Specifies the current BG being evaluated for prioritization
$thisDay$	Specifies the day on the time horizon where shuttle ship and battle group combinations are being prioritized for CONSOL.
$h\_priority$	Highest priority found over all BGs
s_range	Shortest distance range from shuttle ship, s, to bg_priority(bg)
$bg\_stillAvailable()$	Boolean. Determines if a BG is unassigned a corresponding shuttle ship combination for CONSOL.
$lastBG(s)$	The last BG visited by specific shuttle ship, s, for CONSOL
$lastD(s)$	The last day shuttle ship, s, visited a BG
$s\_loc(s,d)$	Shuttle ship, s, sea routes location on specific day, d.
$s\_act(s,d)$	Shuttle ship, s, voyage activity on specific day, d.
$s\_end(s,d)$	Shuttle ship, s, remaining at sea endurance on specific day, d.
$scThreshold(s,c)$	Shuttle ship, s, commodity, c, inventory threshold.

6. Decision Variables

$CONSOL(bg,c,d)$ Captures the stock level of each commodity, c, that was delivered to a BG on a specific day, d.

$SINV(s,c,d)$ Shuttle ship inventory of specific commodity, c, on specific day, d.

$HIT(s,bg,d)$ Indicator of whether a hit occurred between shuttle ship, s, and battle group, bg, on day, d.

7. Replenishment At Sea Prioritization

In order to manage RAS assignments between multiple battle groups, our formulation calculates each battle group's commodity consumption rates and daily commodity inventory level immediately upon model initialization. A potential exists for numerous battle groups to have approximately the same initial requirements, therefore the CLF planning tool must derive a priority for each of them, and assign shuttle ship support accordingly based on their projected demand. To deal with changing inventories, our heuristic calculates, on any given day, a priority for each battle group based on its inventory levels of each of the four commodities. Any commodity whose current inventory level is above 85% does not contribute to the priority, and, consequently, any battle group with all four commodities above this 85% threshold will have a priority of zero (and will not be considered for replenishment) on that day, therefore not assigned a shuttle ship. This serves two purposes; it prevents a battle group from topping off too early along the time horizon and creates a buffer between scheduling consecutive replenishments of the same battle unreasonably too soon, for example two consecutive days. Since inventory levels are calculated for each battle group on each day, our heuristic proceeds by looping through the days in the planning horizon. On each day, the heuristic first determines which battle groups are available for replenishment. This is based on whether the current day is within the range of planning days for the battle group, whether the battle group is not docked (in port) on that day, and whether the "HitOk" box is nonempty for that battle group on that day, on the "BG Voyage Plan" worksheet.

The heuristic then sorts all available battle groups by priority, and attempts to assign available shuttles to replenish the battle groups in order. The following formulation loop is used to determine the battle group service priority, bg_priority(bg) based on the daily bg commodity inventory levels. Recall the prioritization weights assigned to specific commodities, priority(c), which are used to penalize the battle groups more heavily on mission critical requirements. As commodity inventories fall below safety stock levels, and further into extremis stock levels, the scale of the penalties increases by orders of magnitude. This formulation sweeps through each of the battle groups and assigns them a bg_priority(bg) value for each day along the time horizon.

The first part of this routine assigns a bg_priority(bg) based on the depleted commodity stock levels that still remain above safety stock:

```
if bg_inv(bg,c,d)≤bgUpperlim*cap(bg,c)
    bg_priority(bg)=(cap(bg,c)-bg_inv(bg,c,d))
                     *priority(c)
```

After completing the first check, the second part increases the bg_priority(bg) based on any commodity stock levels that fall below the safety stock level, therefore incurring a penalty, forcing a higher service priority:

```
if bg_inv(bg,c,d)≤safety(bg,c)
    bg_priority(bg)=bg_priority(bg)+9*priority(c)*
                     (safety(bg,c)-bg_inv(bg,c,d))
```

The final part accounts for higher penalties incurred due to commodities falling below the extremis stock level, and increases bg_priority(bg) based on these findings:

```
if bg_inv(bg,c,d)≤extremis(bg,c)
      bg_priority(bg)=bg_priority(bg)+90*priority(c)*
                      (extremis(bg,c)-bg_inv(bg,c,d))
Next bg
```

For each battle group, our heuristic considers the shuttles in their original order, and looks for a shuttle that can reach the bg starting at its previous assignment. If no such shuttle is available, the bg is marked “unavailable” for the day and the heuristic moves to the next bg. If a shuttle is found, the heuristic determines if that shuttle needs to hit a port before the replenishment, which is based on the shuttle being less than 20% inventory in any of its commodities. If necessary, the heuristic finds such a port. Once such shuttle has been identified, it is assigned to “HIT” the battle group. The heuristic calculates the amount of each commodity to be transferred, and then adds this to all of the inventory levels for the remaining days in the horizon, and removes this amount from the shuttle inventory. The battle group is marked unavailable for the day.

After defining BG priorities, the preprocessing loop receives data input from the CLF planning tool interface, sets up BG consumption figures and calculates initial BG sawtooth information with no replenishment events. We present this critical algorithm in Figure 4.

```
for d=1 to minDays
   Find active bgs on day d (e.g., d is in bg's available
   days and bg can be hit on d)
      while active bgs remain do
            List bg=highest priority active bg
            Find available shuttle to hit bg
                  if shuttle exits,
                        assign shuttle to hit bg
                        transfer min(shuttle_inv, bg_cap-
                        bg_inv) of each commodity
                  end if
                  make bg inactive
      Loop
Next bg
```

Figure 4. Heuristic algorithm preprocessing loop.

8. Battle Group Replenishment

Initially, we populate all BGs and shuttle ship inventory levels using data that has been extrapolated from the CLF planning tool. Our heuristic algorithm will pre-calculate BG and shuttle ship inventories prior to solving the problem. Additionally, the BG daily consumption numbers are calculated before running any of the decision loops. This action accounts for these figures first, which adjusts the BGs sawtooth levels across the time horizon, in turn simplifying the computational complexity of the algorithm. By running the looping subroutines for BG prioritization our heuristic algorithm is able to determine the order of BG replenishment hits based on urgency of need for each day. The loop will iterate through all BGs while they are available as determined by the BG voyage plans. Inside this loop, critical information is determined such as the availability of a shuttle ship based on cargo on hand, feasibility of a replenishment based on both shuttle ship and BG activities, and feasibility of a replenishment based on the time distance between shuttle ships position of last hit and the position of the next BG.

Next, each BG's initial sawtooth information is processed to determine if their commodity inventory levels are below the preset threshold. If so, they are evaluated for replenishment prioritization and sorted in descending order. The model also will calculate all associated penalties, if any, for inventory shortfalls throughout each day along the time horizon. These figures are affected by each BG's commodity inventory capacities and daily activities. BGs with the highest priority commodities falling below the safety and extremis stock levels are the most heavily penalized and are assigned the highest replenishment scheduling priority and CLF support.

The last overarching loop is related to the cycledays structure that we previously introduced. Our heuristic algorithm evaluates the previous replenishment events executed by shuttle ships and their customer BGs, shuttle ship onboard commodity inventories, proximity of logistics ports to active shuttle ships and BGs, any port loading restrictions in these ports, commodity availability at these ports, BG logistics requirements, and determines whether or not a shuttle ship must proceed either directly or indirectly to follow on replenishment events. This looping structure calls upon sea routes, shuttle ship and BG daily positional data to run the shortest paths algorithm that we previously discussed. It checks the cycleday tuples to see if they are precluded, eliminating infeasible solutions, which also reduces the algorithms run time and complexity. Each BG and shuttle ship combination is examined by looping over the available BGs in sequence, and for each of them looping over each shuttle that can reach that BG, assigning the first shuttle found that can feasibly supply this BG until all available BGs have been considered. Not all BGs may have an assigned shuttle ship for a particularly day, due to the smaller volume of CLF assets. We advance time by one day, and continue running this entire procedure through the end of the time horizon.

When we aggregate all of these key looping structures and supporting code in our algorithm, the heuristic is able to quickly calculate initial feasible solutions to the CLF shuttle-scheduling problem.

IV. ANALYSIS AND CONCLUSIONS CLF PLANNING TOOL EXTENDED WITH HEURISTIC FUNCTIONALITY

A. SCENARIO

The scenario we evaluate in this thesis is derived from a series of experiments conducted at the Navy's Maritime Operations Center-Experimental (MOC-X) facility at Naval Station Norfolk, VA, from 2–5 February 2009. There were a series of three separate events, or Spirals, conducted during the TRIDENT WARRIOR 2009 exercise. During Spiral One experimentation, a seabasing scenario was used to conduct planning for forward-deployed at-sea forces and evaluate the logistic support necessary to sustain operations [Trident Warrior, 2009]. It is here that the CLF planning model was put into operation to optimize at-sea logistics support of deployed BGs. We now revisit the data points collected from this scenario to analyze and compare previous results derived through Hallman's optimization model versus the output our heuristic algorithm generates using the same information.

1. East Africa and Persian Gulf Run

We tested our heuristic algorithm under a stressful scenario composed of four BGs operating in the Commander, Fifth Fleet AOR, more specifically, in the Arabian Gulf and off the coast of eastern Africa. These groups were intentionally separated by long sea lines of communication (SLOC), in order to strain the at-sea logistical support supply lines. The battle groups comprised of a variety of surface combatants, amphibious warships, and a nuclear powered aircraft carrier including, USS ANZIO (CG-68), USS DWIGHT D. EISENHOWER (CVN-69), USS DECATUR (DDG-73), USS FARRAGUT (DDG-99), USS ARLEIGH BURKE (DDG-51), USS BAINBRIDGE (DDG-96), USS HARPERS FERRY (LSD-49), USS SAN JACINTO (CG-56), USS HAWES (FFG-53), USS VELLA GULF (CG-72), USS LABOON (DDG-58), USS WASP (LHD-1), USS SAN ANTONIO (LPD-17), and USS FORT MCHENRY (LSD-

43). Planners can easily active and deactivate BGs using the CLF planning tool's BG-Shuttle Activation worksheet, which is illustrated in Figure 5.

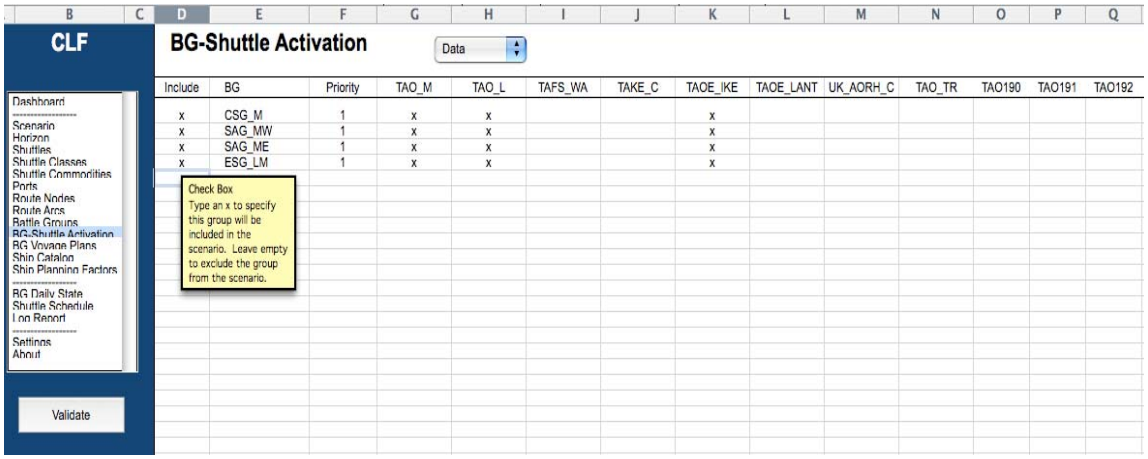
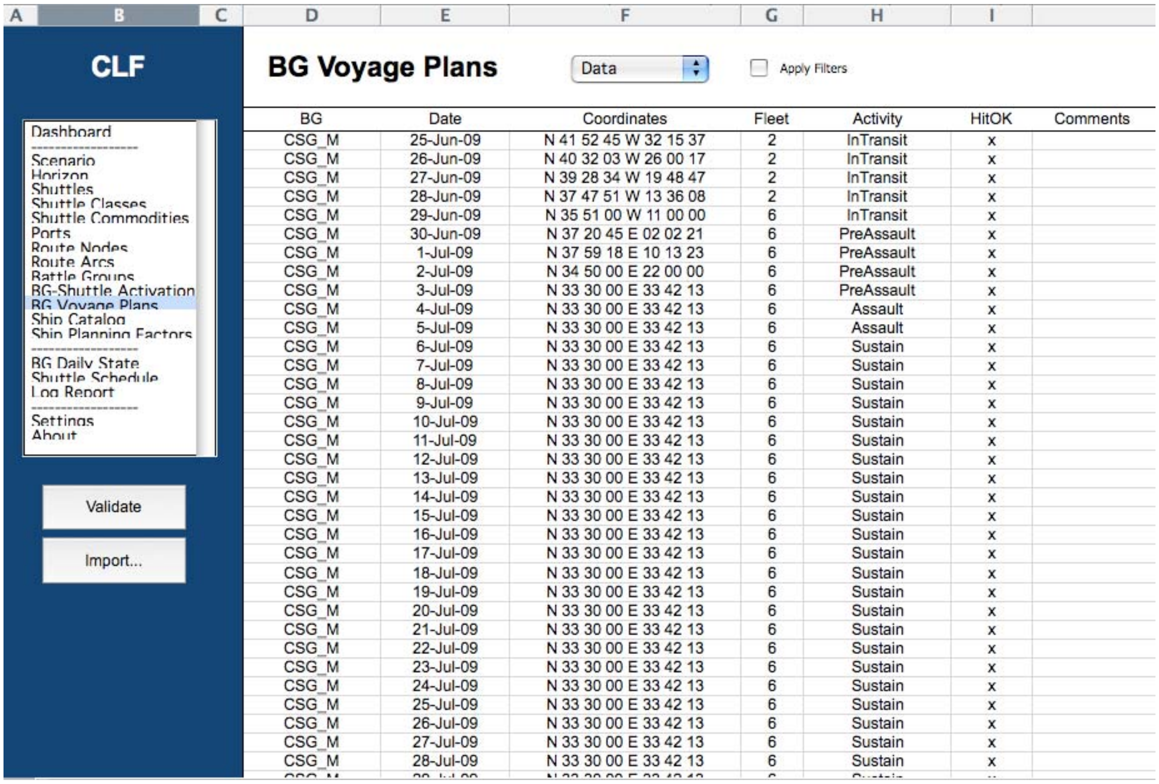


Figure 5. CLF Planning Tool BG-Shuttle Activation worksheet. Prior to running the CLF planning tool, commanders or planners can select or deselect assets for activation and evaluation on this page.

All of the BGs participating in this particular scenario were available to take replenishment at-sea hits throughout every day of the time modeled time horizon, which occurred from 1 November 2009 through 30 November 2009. There voyage plan activities were classified as "On Station" throughout the time horizon as well to facilitate RAS availability. Sample of BG Voyage Plans taken from the CLF planning tool is presented in Figure 6. This meant that none of the BGs was otherwise restricted in daily operations, for example expecting flight operations, being docked in port, conducting an assault, etc. Moreover, the four battle groups were to be logistically supported by three CLF shuttle ships, representative of two separate classes. The shuttle ships committed in this setting were two T-AO Fleet Replenishment Oilers and one T-AOE Fast Combat Support Ship. Fleet Replenishment Oilers lack weapons magazines, and as such, will not have an impact to BG ordnance deliveries. Additionally, T-AOs are also characterized by a limited storage capacity for dry stores commodities. This trade-off is balanced by the T-AO robust capacity to shuttle large quantities of DFM and JP-5 fuels.



BG	Date	Coordinates	Fleet	Activity	HitOK	Comments
CSG_M	25-Jun-09	N 41 52 45 W 32 15 37	2	InTransit	x	
CSG_M	26-Jun-09	N 40 32 03 W 26 00 17	2	InTransit	x	
CSG_M	27-Jun-09	N 39 28 34 W 19 48 47	2	InTransit	x	
CSG_M	28-Jun-09	N 37 47 51 W 13 36 08	2	InTransit	x	
CSG_M	29-Jun-09	N 35 51 00 W 11 00 00	6	InTransit	x	
CSG_M	30-Jun-09	N 37 20 45 E 02 02 21	6	PreAssault	x	
CSG_M	1-Jul-09	N 37 59 18 E 10 13 23	6	PreAssault	x	
CSG_M	2-Jul-09	N 34 50 00 E 22 00 00	6	PreAssault	x	
CSG_M	3-Jul-09	N 33 30 00 E 33 42 13	6	PreAssault	x	
CSG_M	4-Jul-09	N 33 30 00 E 33 42 13	6	Assault	x	
CSG_M	5-Jul-09	N 33 30 00 E 33 42 13	6	Assault	x	
CSG_M	6-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	7-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	8-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	9-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	10-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	11-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	12-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	13-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	14-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	15-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	16-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	17-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	18-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	19-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	20-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	21-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	22-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	23-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	24-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	25-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	26-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	27-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	
CSG_M	28-Jul-09	N 33 30 00 E 33 42 13	6	Sustain	x	

Figure 6. CLF Planning Tool BG Voyage Plans worksheet. Commanders and planners can input voyage plan data for each respective BG, including specific locations and dates, activities, and assign hit ok dates.

a. CLF Planning Tool Optimization Results

Initially, we ran this Eastern Africa and Persian Gulf combined scenario using the legacy CLF planning tool and CPLEX solver to find a feasible solution to the CLF scheduling problem. The computational time totaled approximately five minutes to derive a feasible solution. The results were consolidated into the CLF planning tool's BG Daily State page, which displays the status of each of the BG's commodity levels throughout the entire time horizon. To illustrate the derived replenishment days and respective commodity transfer figures, non-replenishment days have been filtered out. This information presented in Figure 7.

BG Daily State ☑ Apply Filters

BG	Date	Coordinates	DFM	JP5	STOR	ORDN	HitType	HitBy	DFM	JP5	STOR	ORDN
CSG_M	6-Nov-09	N 25 33 44 E 53 18 20	100.0%	100.0%	84.9%	98.4%	consol	TAO_M	9,835.2	24,306.0	69.5	0.0
CSG_M	13-Nov-09	N 28 52 59 E 49 10 29	100.0%	100.0%	63.1%	96.4%	consol	TAO_L	11,474.4	28,357.0	0.0	0.0
CSG_M	20-Nov-09	N 27 39 50 E 50 24 19	100.0%	100.0%	88.2%	100.0%	consol	TAOE_IKE	11,474.4	28,357.0	888.0	107.0
CSG_M	30-Nov-09	N 25 33 44 E 53 18 20	100.0%	100.0%	100.0%	100.0%	consol	TAOE_IKE	16,392.0	40,510.0	812.5	53.5
SAG_MW	1-Nov-09	N 11 31 23 E 46 45 28	100.0%	100.0%	100.0%	100.0%	consol	TAOE_IKE	1,310.4	89.0	8.0	0.3
SAG_MW	9-Nov-09	N 12 02 22 E 51 51 20	100.0%	100.0%	100.0%	100.0%	consol	TAOE_IKE	10,483.2	712.0	64.0	2.0
SAG_MW	18-Nov-09	N 12 02 22 E 51 51 20	100.0%	100.0%	82.0%	98.3%	consol	TAO_L	11,793.6	801.0	27.0	0.0
SAG_ME	1-Nov-09	N 23 03 55 E 64 59 42	100.0%	100.0%	100.0%	99.8%	consol	TAO_M	848.8	34.0	3.0	0.0
SAG_ME	9-Nov-09	N 23 09 38 E 67 07 35	100.0%	100.0%	96.6%	98.5%	consol	TAO_M	6,790.4	272.0	20.5	0.0
SAG_ME	20-Nov-09	N 24 24 25 E 65 22 07	100.0%	100.0%	64.6%	96.6%	consol	TAO_M	9,336.8	374.0	0.0	0.0
SAG_ME	28-Nov-09	N 23 03 55 E 64 59 42	100.0%	100.0%	100.0%	95.2%	consol	TAO_M	6,790.4	272.0	60.5	0.0
ESG_LM	6-Nov-09	N 00 13 11 E 49 50 02	100.0%	100.0%	100.0%	98.7%	consol	TAO_L	18,676.8	6,678.0	174.0	0.0
ESG_LM	15-Nov-09	N 01 03 17 E 55 43 22	100.0%	100.0%	86.6%	96.8%	consol	TAO_M	28,015.2	10,017.0	130.0	0.0
ESG_LM	25-Nov-09	N 06 13 40 E 52 22 58	99.0%	100.0%	58.9%	94.7%	consol	TAO_L	30,055.2	11,130.0	19.0	0.0

Figure 7. CLF Planning Tool BG Daily State. This output page displays all relevant BG status throughout the time horizon, including commodity inventory levels. CONSOL events have been filtered to display relevant data and inventory commodity changes resultant from replenishment transfer.

The BG Daily State output page provides the relevant BG status data for each day along the time horizon. Where replenishment events are scheduled, the commodity levels are augmented by the actual amount of commodities transferred during the replenishment. Unless the servicing shuttle ship is unable to meet the 100% fill rate of a BG’s demand requirements, these figures should reflect 100% capacity on the replenishment day. This output page also displays the name of the servicing CLF shuttle ship and the total quantities of supplies transferred to the BG by commodity type. For example, on 13 November 2009, T-AO_L, the USNS JOHN LENTHAL, delivered 11,474.4 Bbls of DFM, 28,357 Bbls of JP-5, 0 Stons of STOR, and 0 Stons of ORDN, to the BG, CSG_M. Subsequently, CSG_M’s inventory levels for DFM and JP-5 surged to 100% on the day of the replenishment, while the inventory levels for stores and ordnance remained at 63.1% and 96.4%, respectively. Throughout the entire November time horizon, it appears that the BGs receive adequate support for across all types of commodities, with the exception of dry stores. This may be due to the fact that STOR and ORDN are not delivered during every replenishment as opposed to DFM and JP-5. Although none of the commodities for any of the BGs fall below the safety stock level into extremis during this scenario, the below sawtooth chart captures the STOR stock changes throughout the time horizon, showing that each BG STOR level falls below the safety stock level at least once (in this case, below 50% capacity) Figure 8. This may be due to limited stores availability at logistics hubs, or BG demands that exceed CLF shuttle ship capacity.

Figure 8. Stores commodity inventory levels for all four BGs across the entire scenario time horizon. During the time horizon, each BG stores inventory levels cross the safety stock threshold level once.

b. CLF Planning Tool Solved Using Heuristic Functionality

We now solve the identical East Africa and Arabian Gulf scheduling scenario that was introduced in the above section using our heuristic algorithm, which has been built in as an extension to the CLF planning tool. To switch solving engines, users can simply open the CLF planning tool's "Scenario" page, and use a drop down menu to select the "Heuristic" solver. By comparison to CPLEX, using the heuristic algorithm to solve the scheduling program only takes seconds to determine an initial, feasible scheduling solution for the same problem. The output scheduling solution is automatically exported into a heuristic log file that is easily accessible and available to staff planners. Similarly to the BG Daily State page, the heuristic log file displays the shuttle ship and BG tuples for each of the derived CONSOL days, as well as the amount of each commodity that is transferred to the BG during the replenishment event. The heuristic log file for this scenario is presented in Figure 9.

```
HIT( 'TAO_M','CSG_M','03NOV09' ) = 1 ;
  CONSOL('CSG_M','03NOV09','DFM' ) = 4917.59999999999 ;
  CONSOL('CSG_M','03NOV09','JP5' ) = 12153 ;
  CONSOL('CSG_M','03NOV09','STOR' ) = 177 ;
HIT( 'TAO_M','CSG_M','06NOV09' ) = 1 ;
  CONSOL('CSG_M','06NOV09','DFM' ) = 4917.6 ;
  CONSOL('CSG_M','06NOV09','JP5' ) = 12153 ;
  CONSOL('CSG_M','06NOV09','STOR' ) = 177 ;
HIT( 'TAO_M','CSG_M','09NOV09' ) = 1 ;
  CONSOL('CSG_M','09NOV09','DFM' ) = 4917.6 ;
  CONSOL('CSG_M','09NOV09','JP5' ) = 12153 ;
  CONSOL('CSG_M','09NOV09','STOR' ) = 177 ;
HIT( 'TAO_M','CSG_M','15NOV09' ) = 1 ;
  CONSOL('CSG_M','15NOV09','DFM' ) = 4917.6 ;
  CONSOL('CSG_M','15NOV09','JP5' ) = 12153 ;
  CONSOL('CSG_M','15NOV09','STOR' ) = 72 ;
HIT( 'TAO_M','CSG_M','18NOV09' ) = 1 ;
  CONSOL('CSG_M','18NOV09','DFM' ) = 4917.6 ;
  CONSOL('CSG_M','18NOV09','JP5' ) = 12153 ;
  CONSOL('CSG_M','18NOV09','STOR' ) = 92 ;
HIT( 'TAO_M','CSG_M','22NOV09' ) = 1 ;
  CONSOL('CSG_M','22NOV09','DFM' ) = 6556.8 ;
  CONSOL('CSG_M','22NOV09','JP5' ) = 16204 ;
  CONSOL('CSG_M','22NOV09','STOR' ) = 220 ;
HIT( 'TAO_M','CSG_M','26NOV09' ) = 1 ;
  CONSOL('CSG_M','26NOV09','DFM' ) = 6556.8 ;
  CONSOL('CSG_M','26NOV09','JP5' ) = 16204 ;
  CONSOL('CSG_M','26NOV09','STOR' ) = 60 ;
HIT( 'TAO_M','CSG_M','30NOV09' ) = 1 ;
  CONSOL('CSG_M','30NOV09','DFM' ) = 6556.8 ;
  CONSOL('CSG_M','30NOV09','JP5' ) = 16204 ;
  CONSOL('CSG_M','30NOV09','STOR' ) = 60 ;
HIT( 'TAO_M','SAG_MW','13NOV09' ) = 1 ;
  CONSOL('SAG_MW','13NOV09','DFM' ) = 5241.60000000001 ;
  CONSOL('SAG_MW','13NOV09','JP5' ) = 356 ;
  CONSOL('SAG_MW','13NOV09','STOR' ) = 32 ;
HIT( 'TAO_M','SAG_MW','19NOV09' ) = 1 ;
  CONSOL('SAG_MW','19NOV09','DFM' ) = 7862.40000000001 ;
  CONSOL('SAG_MW','19NOV09','JP5' ) = 534 ;
  CONSOL('SAG_MW','19NOV09','STOR' ) = 48 ;
```

Figure 9. Heuristic Initial Feasible Solution. Derived scheduling solution to the East Africa and Arabian Gulf combined scenario using the heuristic algorithm. This log details the tuples created and the respective commodity amounts CONSOL'd during replenishment events.

The heuristic log file, heur.log, is automatically generated when the "Solve" radio button is selected in the CLF planning tool. To interpret data, we will use the first event listed as an example. During this event, the shuttle ship, TAO_M, replenishes the BG, CSG_M (EISENHOWER CSG), on 03 November 2009. During this event, 4,917 Bbls of DFM, 12,153 Bbls of JP-5, and 177 Stons of STOR will be transferred to the station ship. Recall that in our model, all of the BGs demands are aggregated into one overall requirement, and then the shuttle ship fills that demand by delivering all of the required supplies to the BG's station ship. We assume that the station ship will then later disseminate them among the individual assets that make up the BG. The follow-on event, scheduled for 6 November 2009, is identical to the first replenishment. The figures generated by the heuristic algorithm are consistent with those generated by the CPLEX feasible results. For example, the CPLEX results schedule the first CONSOL of CSG_M with TAO_M on 6 November 2009 (recall figure 6). During that event, CSG_M receives 9,835.2 Bbls of DFM and 24,306 Bbls of JP-5. Similarly, the heuristic algorithm schedules a CONSOL between the same shuttle ship and BG on 3 November 2009 and again on 6 November 2009. During these two events, CSG_M receives 9,835.2 Bbls of DFM and 24,306 BBls of JP-5, which are equivalent amounts of the same commodities. While this holds true for this particular target date and these commodities, the amounts will not always sum to be equivalent in all cases until the end of the time horizon. Taking STOR for example. By 20 November 2009, the optimization model shows that CSG_M will have received 957.5 Stons of dry stores. By comparison, the heuristic approach yields a total stores transfer of 695 Stons of dry stores by 18 November 2009. This can be attributed to the relaxations characteristic of the heuristic algorithm, as compared to the optimized results of the model running CPLEX, which will schedule less events if possible, and plus-up inventories to optimal capacities, and feature the transfer of greater amounts of commodities per replenishment event. These variations can also be attributed to the penalties associated for each type of commodity, class of CLF shuttle servicing he BG, and availability of ports and commodities at those ports.

Our heuristic model also generates a log file that allows us to quickly generate corresponding sawtooth chart for visual representation of commodity stock levels throughout the scenario. All of the commodities corresponding sawtooth charts are provided below. Note that all of the BG's data are aggregated by commodity type.

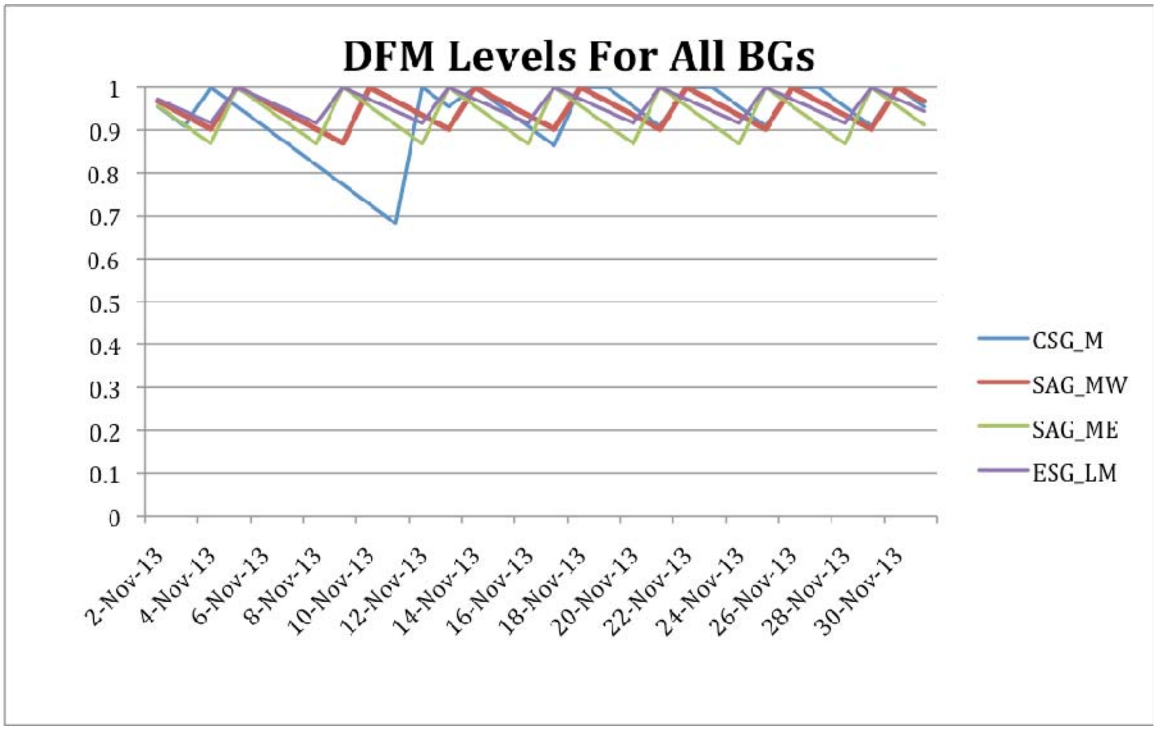


Figure 10. DFM levels for all BGs using the heuristics algorithm output.

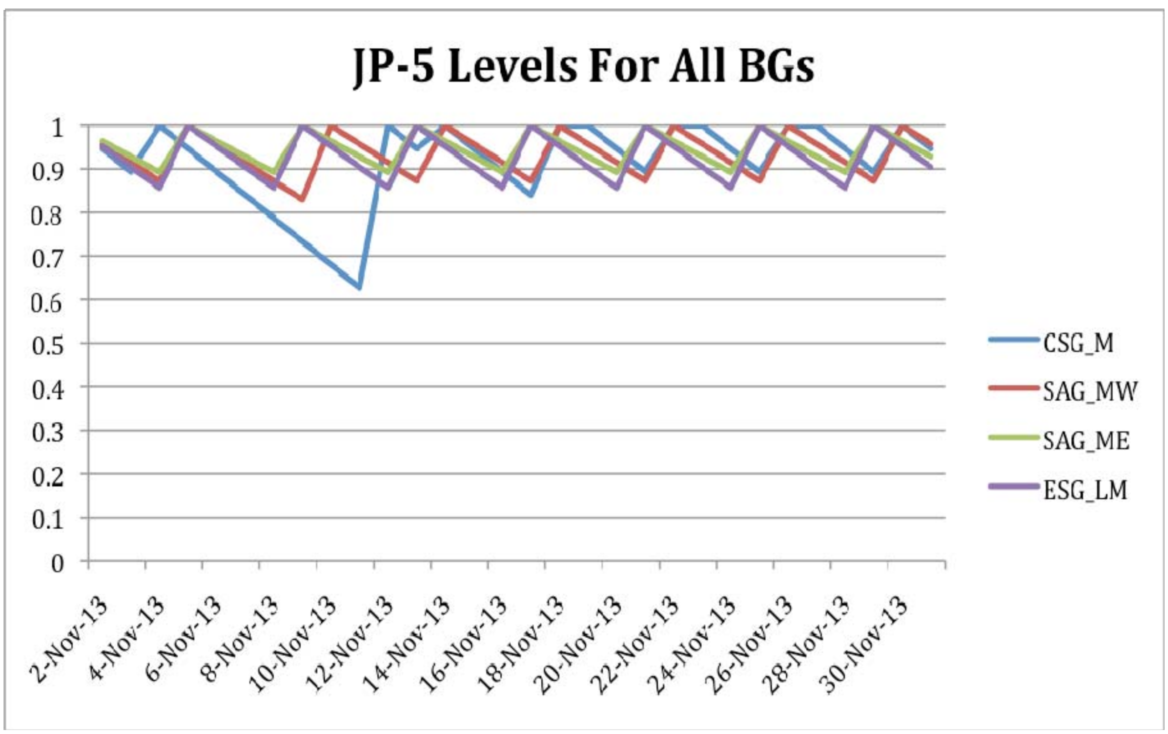


Figure 11. JP-5 levels for all BGs using the heuristics algorithm output

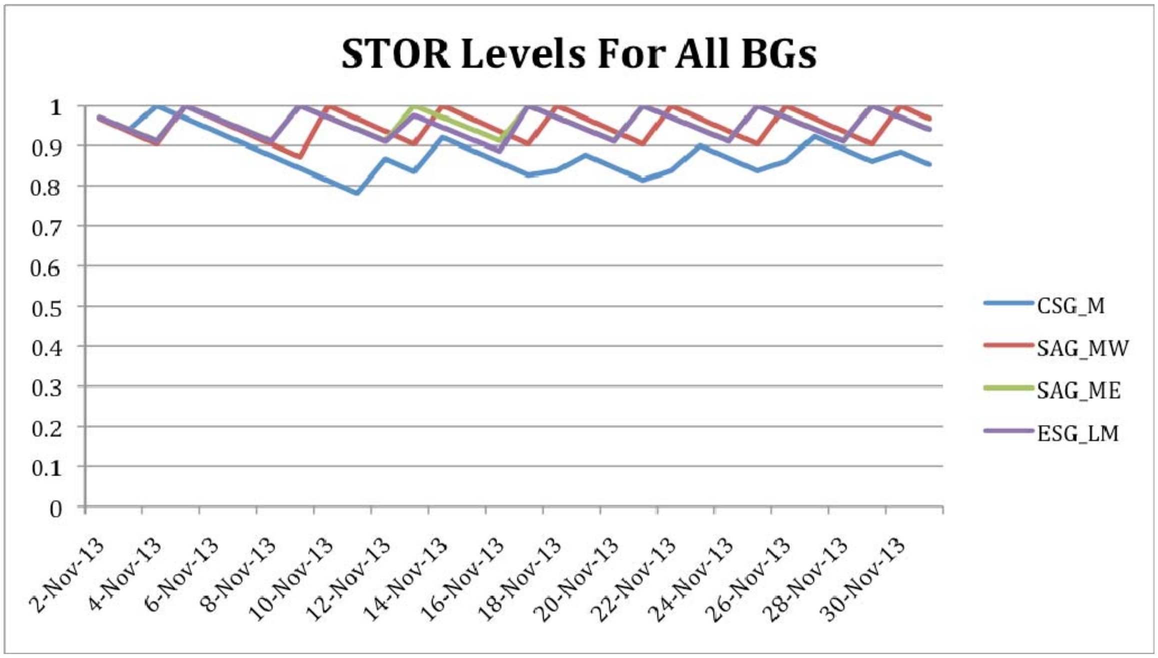


Figure 12. STOR levels for all BGs using the heuristic algorithm output

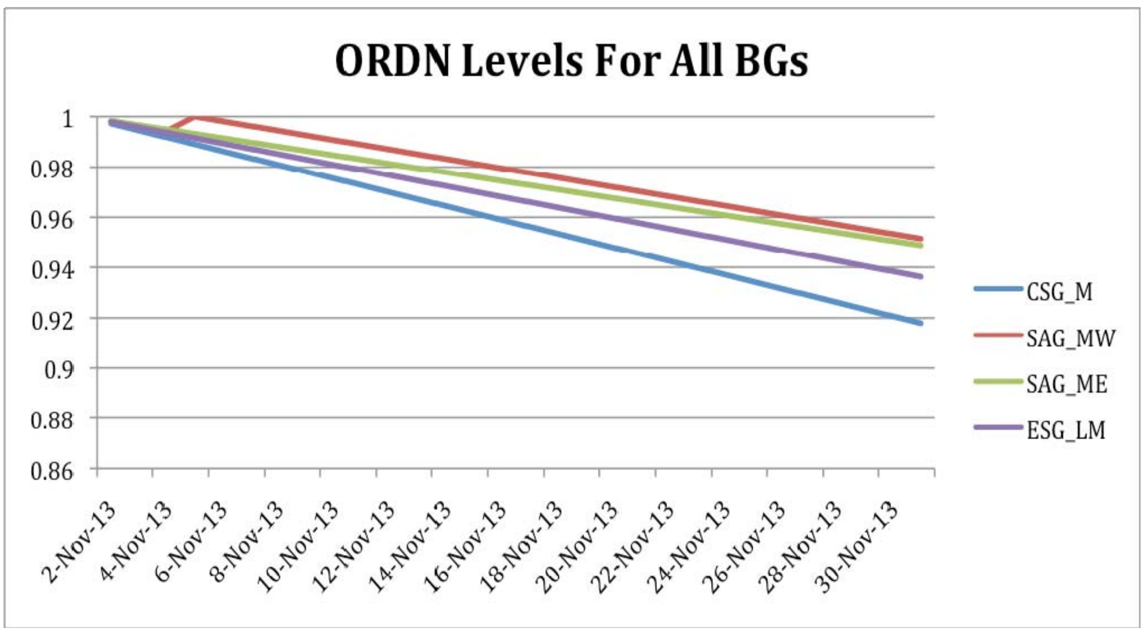


Figure 13. ORDN levels for BGs using the heuristic algorithm output

2. Caribbean Scenario

To further stress our models, we also ran a Caribbean scenario using the historical data from TRIDENT WARRIOR 09. This scenario was comprised of five battles groups supported by three CLF shuttle ships through the Caribbean. This included three Guided Missile Destroyers, two Guided Missile Frigates, and Amphibious Assault Ship, and a High Endurance Hamilton-class U.S. Coast Guard Cutter, supported by the USNS JOHN LENTHALL (T-AO 189), USNS LEWIS AND CLARK (T-AKE 1), and RFA WAVEKNIGHT (A390) (Royal Fleet Auxiliary fast fleet tanker). The CLF planning tool dashboard provides us with a detailed map of the AOR, including BG tracks, CLF track, the sea routes network, and other valuable information, which is provided below.

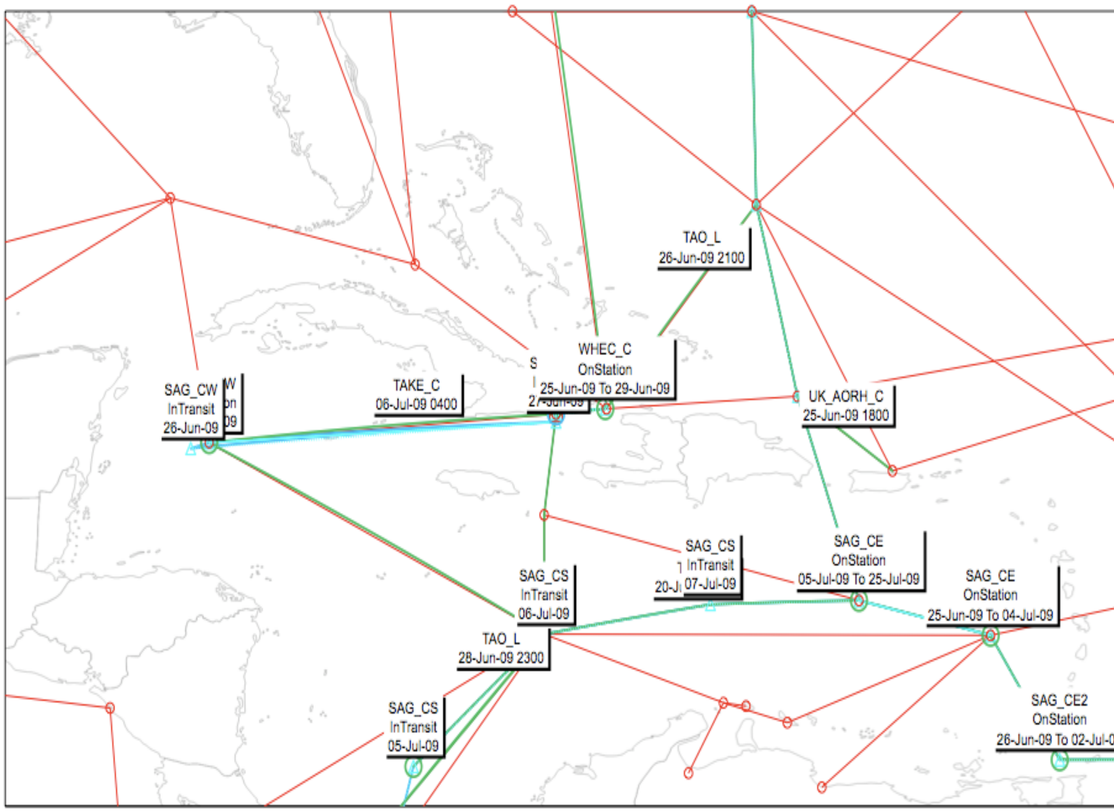


Figure 14. Dashboard map representation of the Caribbean scenario.

a. CLF Optimization Sawtooth

Again, we ran the CPLEX solver to generate feasible results from the legacy CLF planning tool and can easily see from the generated sawtooth charts that the CLF fleet activated in that AOR would adequately support the five BGs in the Caribbean. The below figure is representative of the DFM sawtooth for all of these BGs throughout the TRIDENT WARRIOR 09 timing horizon, Figure 15. In this example, it appears that BG SAG_CE's DFM inventory level drops below safety stock for approximately five days prior to being replenished and SAG_CW has one day of DFM below safety stock level before a replenishment as well.

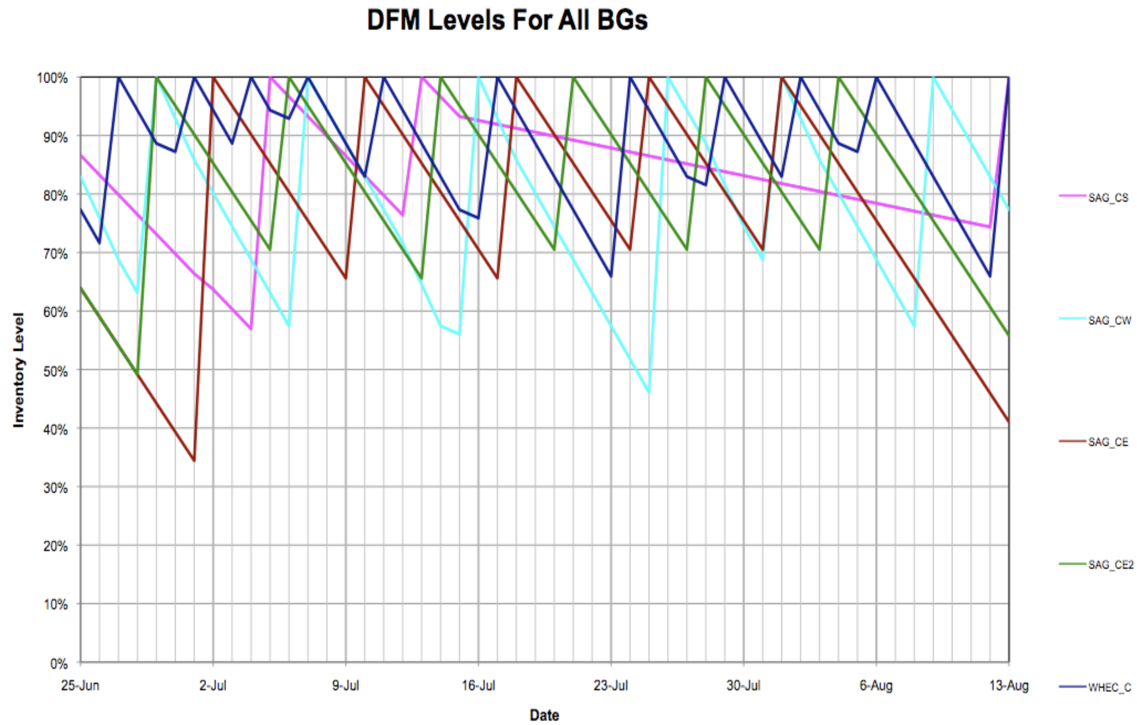


Figure 15. DFM Sawtooth Chart across five battle groups operating in the Caribbean during TRIDENT WARRIOR 2009, Spiral One.

b. Caribbean Scenario Solved by the Heuristic Functionality

After running the heuristic solver for this same scenario, it is evident that the sawtooth charts bare striking similarities. Specifically, the long unsupported stretch of time between 15 JUL 09 through nearly the end of the time horizon for SAG_CS.

Also, there is a marked similarity with the downward slopes for SAG_CE on both charts. The DFM sawtooth chart generated by the heuristic algorithm is provided for direct comparison, Figure 16. The heuristic algorithm generates results that are realistic for the first part of the planning horizon. Unfortunately, we see in the last third that at least one BG suffers due to the myopic approach of our greedy algorithm.

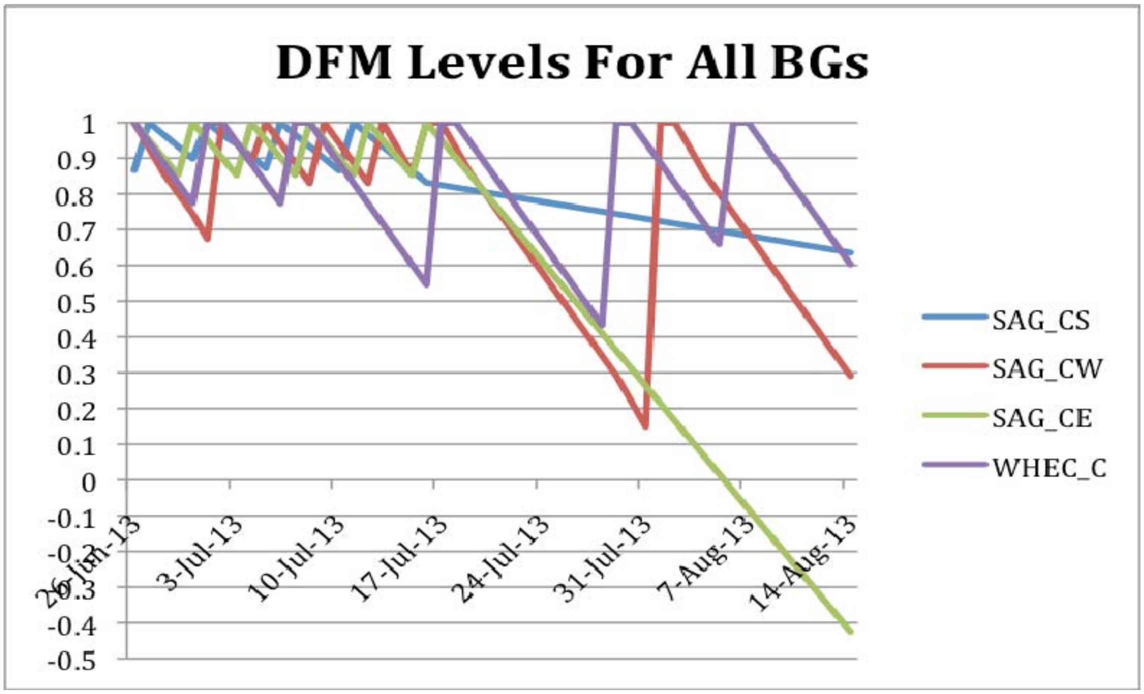


Figure 16. DFM levels for all BGs operating in the Caribbean across the time horizon. Note that derived data is similar to output from the model running the CPLEX solver, with the exception of SAG_CE in the latter third of the horizon.

B. CONCLUSION

1. Summary

Generating feasible sustainment plans for deployed battle groups prior to mission execution is highly complicated and demanding. Fleet staffs are charged with developing these plans using antiquated methods without the use of mathematical programming or automated decision support tools. Current methods do not account for anywhere near the level of fidelity that has been presented in support of the CLF planning tool. By design, the tool presented here, along with our heuristic algorithm, can recalculate feasible solutions as real world changes occur, significantly improving on the speed and quality of the results derived by current capabilities in fleet use today. The CLF planning tool provides Combatant Commanders with the resources that will give them the ability to generate feasible solutions to their CLF scheduling problems within a short amount of time. Moreover, with the added functionality of the heuristics algorithm that we have presented, fleet staffs and planners can generate initial feasible solutions in a matter of seconds. In the high-paced staff environment, the ability to quickly generate virtually error-free, supportable, mathematically substantiated plans is exceedingly desirable.

2. Future Research

Our greedy heuristic algorithm is just one way to assign shuttles to BGs and schedule RAS events over a given horizon. For example, changing the order of the inner loops to check, say, each shuttle ship in order, and assign it throughout its available horizon, would change the results, and possibly lead to better schedules. More advanced heuristic algorithms, such as genetic algorithms, simulated annealing, etc., might provide some improvement as well.

Ultimately, the goal is to have these heuristic algorithms to provide very efficient schedules in a variety of scenarios, but, as an intermediate step, we suggest tuning the heuristics so they provide initial feasible solutions to commercial off-the-shelf optimization software in order to improve its performance while solving these complex scheduling problems.

a. Change in Prioritization Function

Our heuristic algorithm relies on a series of loops to determine the prioritization of shuttle ship to battle group tuple assignments. We chose to iterate through each battle group to determine the priority in descending order from highest to lowest. In our analysis, we did not develop a model where our algorithm would iterate through a list of available shuttle ships first, then assign battle groups to them. This may have a different impact to our CONSOL tuple assignments and is worth further exploration.

b. Rule Changes to Resupply Thresholds

Further analysis can be conducted after changes are made to BG replenishment requirements, such as when a shuttle ship can be assigned to CONSOL a BG based on the BG's inventory levels. Moreover, studies should be conducted to see what effect changes in thresholds would have on BGs and shuttles ship ability to pull into port. This can be extended even further to see what effects these rule changes would have on global fleet scheduling policies.

APPENDIX: HALLMAN FORMULATION

A. CLF PLANNING TOOL FORMULATION

The optimization model presented in this appendix is taken directly from Hallman [2009], which is an extension of the model in Brown and Carlyle [2008]:

1. Indices [Cardinality]

$v \in V$	Class of shuttle ship [~5]
$s \in S$	Shuttle ship [~25]
$v(s)$	Class of shuttle ship s
$s \in S_v \subseteq S$	Shuttle ships in class v
$p \in P$	Port available to load shuttle ships [~35] (alias *px*)
$bg \in BG$	Battle group [~13] (alias *bx*, *by*)
$d \in D$	Day [~181] (alias *dx*, *dy*, *dh*)
$dp \in DP_{bg} \subseteq D$	Days a battle group visits some port to load commodities
$dp \in D_{bg} \subseteq D$	Deployed days for battle group
$dh \in DH_{bg,d} \subseteq D$	For deployment day, d, set of deployment days since the later of the start of the planning horizon and latest port call.
$c \in C$	Commodity group (DFM, JP5, STOR, ORDN) [~4]
$\hat{c} \subseteq C$	Dry commodity subject to load fraction restrictions (STOR, ORDN) (alias $\hat{c}$)

For economy of exposition, we assume (*bg*, *d*) pairs are defined only for $d \in D_{bg}$

2. Provided Data [Units]

$spdSHUTTLE_S$ Speed of shuttle ship s [nm/day]

$inptTAT$ Time to reload shuttle ship in port [days]

$portok4s_{s,p}$ Binary indicator that shuttle ship s can reload at port p [binary]

$legdays_{s,bg,d,p}$ Shuttle ship s transit time at speed $spdSHUTTLE_s$ to or from bg position on day d and port p following given sea routes and/or BG tracks [days]

$cycledays_{s,bg,d,p,bx,dx}$ Days required for shuttle ship s to depart bg on day d, reload at port p (or proceed directly), and then rendezvous with bx on day dx [days]

$directdays_{s,bg,d,bx,dx}$ The number of steaming days for shuttle s to transit from the position of bg on day d directly to the position of bx on subsequent day dx (i.e., without reloading in any port). (Policy limits may govern the minimum or maximum days allowed between these planned events).

$useBG_{bg,d,c}$ Consumption by bg during day d of commodity c [c-units]

$mxload_{bg,c}$ Maximum capacity of bg to carry commodity c [c-units]

$init\_load_{bg,c}$ bg inventory of commodity c on first deployed day [c-units]

$init\_lat_s, init\_long_s, init\_state_s$ Optional pre-positioning of shuttle s either "empty" and requiring routing to a port, or "loaded" and requiring routing to a customer battle group.

$safety_c$ Minimum desired fraction of $mxload_{bg,c}$ to be held at all times

[fraction]

$extremis_c$ — Extreme minimum desired fraction of $mxload_{bg,c}$ to be held at all times, $extremis_c \le safety_c$ [fraction].

$hitOK_{bg,d}$ — Logical indicator if bg can CONSOL on day d [binary]

$capacity_{s,c}$ — Shuttle ship s capacity to deliver commodity c [c-units]

$mnfrac_{\hat{c}}, mxfrac_{\hat{c}}$ — Minimum, maximum fraction of T-AKE dry capacity that must be loaded with dry commodity $\hat{c}$ [fraction]

$safety\_penalty_c$ — Penalty per deficit unit of desired storage below safety-stock held by any BG [penalty per c-unit]

$extremis\_factor$ — Multiplier (>1, e.g. 10) for penalty per deficit unit of desired storage below extremis held by any BG [dimensionless]

$negative\_factor$ — Multiplier (>1 $extremis\_factor$, e.g. 1000) for penalty per deficit unit of desired storage below zero held by any BG [dimensionless]

win — Minimum number of days between bg consol

3. Derived Data

$mxconsol_{s,bg,c}$ — Maximum delivery shuttle ship s can make to bg on any day of commodity c [c-units]. This is defined as:

$$\min\{mxload_{bg,c}, capacity_{s,c}\}.$$

In addition, for T-AKE shuttle ships and dry commodities $\hat{c}$ sharing dry storage, and subject to limits on the minimum and maximum fractions of dry capacity that must be carried in every T-AKE load, this is restricted to:

$$\min\{mxload_{bg,c}, \min[mxfrac_{\hat{c}}, 1-\sum_{\tilde{c}\neq\hat{c}} mnfrac_{\tilde{c}}] * capacity_{s,\hat{c}}\}$$

or, the maximum permitted T-AKE load of dry commodity $\hat{c}$, or the amount of commodity $\hat{c}$ that can be loaded after the minimum loads of other dry commodities $\tilde{c} \neq \hat{c}$ sharing dry storage are loaded. $cycledays_{s,bg,d,p,bx,dx}$ gives the number of days required for shuttle ship s to depart bg on day d to reload at some port p (or proceed directly) and then rendezvous with bx on day dx:

$$\min\left\{\begin{array}{l} \infty, \min\left[\begin{array}{l} \min(legdays_{s,bg,d,p} + inptTAT + legdays_{s,bx,dx,p}) \\ dx \geq legdays_{s,bg,d,p} \\ +inptTAT \\ +legdays_{s,bx,dx,p} \end{array}\right] \\ p \mid portok4s_{s,p} \end{array}\right\}$$

Note that this admits a cycle with slack time (or, "shuttle waiting time") $dx - d - cylcedays_{s,bg,d,bx,dx} \geq 0$, and that because of the relative motion of a shuttle ship and a BG over navigable sea route, and their daily proximity to ports and to each other, there will be cases in which planning for a shuttle to wait for this amount of time is better than restricting plans to have no such slack.

4. Decision Variables

$VISIT_{bg,d}$	Binary indicator that at least one shuttle visits bg on day d
$HIT_{s,p,bg,d}$	Binary indicator of shuttle s coming from port p to a CONSOL visit of bg on day d (depends on $hitOK_{bg,d}$) (one port is called "direct" and indicates that the associated CONSOL visit follows some prior one without an intervening port call to reload.) (Restriction of shuttle s initial location and state may preclude some HIT events. E.g., from some initial location, an empty shuttle would have to transit to a port, reload, then transit to a bg location by day d.)

$SLOAD_{s,d,c}$	Shuttle s commodity c contents at end of day d [c-units]
$CONSOL_{s,bg,d,c}$	Amount of shuttle s delivery to bg on day d of commodity c [c-units]
$SHORTAGE_{bg,d,c}$	Amount of inventory deficiency of c for bg, at end of day d [c-units]
$EXTREMIS_{bg,d,c}$	Amount of extreme deficiency of c for bg, at end of day d [c-units]
$NEGINV_{bg,d,c}$	Magnitude of negative inventory of c for bg at end of day d, has this [c-units]

5. Formulation

s.t.
$$SLOAD_{s,d-1,c} + \sum_{\substack{p \in P-\{direct\},\\ bg \in BG}} capacity_{s,c} HIT_{s,p,bg,d+legdays_{s,bg,d,p}}$$

$$\geq \sum_{bg \in BG} CONSOL_{s,bg,d,c} + SLOAD_{s,d,c} \qquad \forall s \in S, d \in D-\{1\}, c \in C \qquad (1)$$

$$\sum_{\substack{s \in S,\\ dh \in DH_{bg,d}}} CONSOL_{s,bg,dh,c}$$

$$\leq \sum_{dh \in DH_{bg,d}} useBG_{bg,dh,c} + [mxload_{bg,c} - init\_load_{bg,c}]_{d=\arg\min\{D_{bg}\}}$$

$$\forall bg \in BG, d \in D_{bg}, c \in C \qquad (2)$$

$$\sum_{\substack{s \in S,\\ dh \in DH_{bg,d}}} CONSOL_{s,bg,dh,c} + SHORTAGE_{bg,d,c} + EXTREMIS_{bg,d,c} + NEGINV_{bg,d,c}$$

$$\geq \sum_{dh \in DH_{bg,d}} useBG_{bg,dh,c} - (1 - safety_c) mxload_{bg,c}$$

$$\forall bg \in BG, d \in D_{bg}, c \in C \qquad (3)$$

$$CONSOL_{s,bg,d,c} \leq mxconsol_{s,bg,c} HIT_{s,bg,d} \qquad \forall s \in S, \forall bg \in BG, d \in D_{bg}, c \in C \qquad (4)$$

$$\sum_{p \in P} HIT_{s,p,bg,d} \leq 1 \qquad \forall s \in S, bg \in BG, d \in D \qquad (5)$$

$$HIT_{s,p,bg,d} + \sum_{\substack{bx \in BG, \\ px \in P, dx \in D_{bx} \\ dx - d < cycledays_{s,bg,d,px,bx,dx}}} HIT_{s,px,bx,dx} \leq 1 \qquad \forall s \in S, p \in P, bg \in BG, d \in D_{bg} \qquad (6)$$

$$\sum_{\substack{s \in S_v, \\ p \in P, \\ d \leq dx \leq d + win}} HIT_{s,p,bg,dx} \leq 1 \qquad \forall v \in V, bg \in BG, d \in D_{bg} \qquad (7)$$

$$\sum_{\substack{p \in P, \\ bg \in BG}} HIT_{s,p,bg,d} \leq 1 \qquad \forall s \in S, d \in D \qquad (8)$$

$$\sum_{\substack{s \in S_v, \\ p \in P}} HIT_{s,p,bg,d} \leq VISIT_{bg,d} \qquad \forall v \in V, bg \in BG, d \in D_{bg} \qquad (9)$$

$$\sum_{p \in P} HIT_{s,p,bg,d} \leq VISIT_{bg,d} \qquad \forall s \in S, bg \in BG, d \in D \qquad (10)$$

$$\sum_{d - win \leq dx \leq d} VISIT_{bg,dx} \leq 1 \qquad \forall bg \in BG, d \in D_{bg} \qquad (11)$$

$$VISIT_{bg,d} \in \{0,1\} \qquad \forall bg \in BG, d \in D_{bg}$$

$$HIT_{s,p,bg,d} \in \{0,1\} \qquad \forall s \in S, p \in P, bg \in BG, d \in D_{bg}$$

$$0 \leq SLOAD_{s,d,c} \leq capacity_{s,c} \qquad \forall s \in S, d \in D, c \in C$$

$$0 \leq CONSOL_{s,bg,d,c} \leq mxconsol_{s,bg,c} \qquad \forall s \in S, bg \in BG, d \in D_{bg}, c \in C$$

$$0 \leq SHORTAGE_{bg,d,c} \leq (safety_c - extremis_c) * mxload_{bg,c}$$

$$\forall bg \in BG, d \in D_{bg}, c \in C$$

$$0 \leq EXTREMIS_{bg,d,c} \leq extremis_c * mxload_{bg,c} \qquad \forall bg \in BG, d \in D_{bg}, c \in C$$

$$0 \leq NEGINV_{bg,d,c} \qquad \forall bg \in BG, d \in D_{bg}, c \in C \qquad (12)$$

$$\begin{aligned}
&\underset{\substack{VISIT, HIT,\\ SLOAD, CONSOL,\\ SHORTAGE, EXTREMIS, NEGINV}}{MIN} \sum_{s\in S, bg\in BG, d\in D_{bg}, c\in C} safety_penalty_c * CONSOL_{s,bg,d,c}\\
&+ \sum_{bg\in BG, d\in D_{bg}, c\in C} safety_penalty_c * SHORTAGE_{bg,d,c}\\
&+ \sum_{bg\in BG, d\in D_{bg}, c\in C} extremis_factor * safety_penalty_c * EXTREMIS_{bg,d,c}\\
&+ \sum_{bg\in BG, d\in D_{bg}, c\in C} negative_factor * safety_penalty_c * NEGINV_{bg,d,c}
\end{aligned} \tag{13}$$

6. Discussion

Inequalities (1) account for shuttle cargo contents day by day. Inequalities (2) limit day-by-day cumulative CONSOL volumes of each commodity to the cumulative usage of each BG through the end of that day. We assume that on the first planning day, each BG contains some stated initial load quantity. Thereafter, daily use is deducted, and replenishments from port calls of those commodities offered and shuttle CONSOLs are added. Elastic inequalities (3) reckon cumulative inventory state of each commodity at the end of each planning day, and compare this to the cumulative usage less desired safety-stock level at the end of that day, representing any shortage, extreme shortage, or negative inventory required to reconcile this state. Each inequality (4) limits the CONSOL volume transferred from a shuttle ship, to a BG, on some given day, to be zero unless a replenishment event takes place. Constraints (5) allow at most one port source for each CONSOL. This "port" may be "direct," indicating no preceding port call. Constraints (6) restrict successive shuttle rendezvous with battle groups so that each such visit is followed by sufficient time to cycle to a port for re-supply. Each constraint (7-11) permits a shuttle to engage in at most one activity on a given day. Variable domains are stated by constraints (12). The objective (13) expresses a penalty with a component for any shortage below safety-stock, extreme shortage below minimum stock, and any negative inventory as well as less rewards for commodity volume delivered. The rewards here are 10 percent of the safety stock shortage penalties, and attract maximal delivered volumes, rather than merely deliveries to avoid shortages. The model can schedule a single shuttle ship sortie from port to make many separate CONSOL visits, perhaps to different battle groups.

LIST OF REFERENCES

Borden, K. (2001). "*Optimizing the number and employment of combat logistics force shuttle ships, with a case study of the T-AKE ship,"* Master's thesis, Naval Postgraduate School.

Brown, G. and Carlyle, W. M. (2008). Optimizing the US Navy's Combat Logistics Force. *Naval Research Logistics*, 55, pp. 800–810.

Cardillo, J. A. (2004). "Optimizing global operations plans for the combat logistics force," Master's thesis, Naval Postgraduate School.

FGM Inc. "Matching Warfighter Mission Needs to Employment Assets Worldwide," (2007). *GAMS*. Retrieved February 12, 2010, from www.fgm.com.

General Algebraic Modeling System (GAMS) Development Corporation. (2009). *GAMS*. Retrieved February 12, 2010, from www.gams.com.

Hallmann, F. (2009). "Optimizing operational and logistical planning in a theater of operations," MS Thesis in Operations Research, Naval Postgraduate School.

Microsoft Corporation (2008). "Excel 203 Visual Basic for Applications (EXCEL/VBA)". Retrieved February 12, 2010, from www.microsoft.com.

Morse, T. C. (2008). "Optimization of combat logistics force required to support major combat operations," Master's thesis, Naval Postgraduate School.

Navy Sea Systems Command. "Strategic Business Plan," (2009). Last accessed April, 1, 2010, from, from www.navsea.navy.mil.

Trident Warrior/OLC2 Public Affairs (2009). "Trident Warrior 2009 Completes Spiral 1 Experimentation." Retrieved March 21, 2010, from www.chips.navy.mil

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Professor Matt Carlyle
   Naval Postgraduate School
   Monterey, CA

4. Professor Gerald Brown
   Naval Postgraduate School
   Monterey, CA

5. Jeff Kline, CAPT USN (ret), Operations Research Department
   Naval Post Graduate School
   Monterey, CA

6. Carol O'Neal, CAPT USN (ret), Operations Research Department
   Naval Post Graduate School
   Monterey, CA

7. Patrick Burson, CDR USN, Operations Research Department
   Naval Post Graduate School
   Monterey, CA

8. Dr. Donald K. Wagner
   Office of Naval Research
   Mathematical, Computer and Information Sciences (Code 311)
   Arlington, VA

9. Mr. Jonathan Kaskin, OPNAV N42
   Director, Strategic Mobility/Combat Logistics Division
   Arlington, VA

10. Andres Diaz, LCDR USN
    Naval Post Graduate School
    Monterey, CA